

**CRANFIELD UNIVERSITY**

**ALLAN ROBINSON**

**INTEGRATED SYSTEMS MODELLING OF THE INTERACTION  
BETWEEN WATER RESOURCES AND AGRICULTURE**

**INTERNATIONAL ECOTECHNOLOGY RESEARCH CENTRE  
(SIMS)**

**Ph.D. THESIS**



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**Supervisor: Professor P M Allen**

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## ABSTRACT

Environmental problems associated with the use of water are inherently complex, involving the interaction of several different systems. Further, there is often limited data on the interaction, because of its location between disciplines. In order to study these problems in a quantitative, policy relevant way, a numerical model is required that integrates the different systems and is tailored to contain the processes important to the interaction.

A numerical water resource system model is developed to study the problems associated with the interaction between agriculture and water. The model integrates an econometric model of farmer behaviour with a dynamic model of water flow and solute transport. The Argolid valley in Greece represents an area where severe environmental problems have arisen as a result of the overexploitation of groundwater for agriculture. When applied to the Argolid valley the water resource system model reproduces the evolution of the environmental problems that have arisen. It is then demonstrated that the model can be used to investigate some future scenarios and policy options related to the environmental problems that have developed.

The main contribution of this research is to demonstrate that a properly designed numerical model that reproduces the dynamic interaction between human behaviour and the physical environment can enable the exploration of the evolution of environmental problems despite a lack of calibration data. Having achieved this the model can then be used in a policy relevant way to investigate the implications from a range of different, possible policy options.

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## LIST OF NOTATIONS

$\Delta a$	quality of fit to crop share data.
$\Delta A_k$	area
$\Delta t$	timestep;
$\Delta x$	grid size in the x direction;
$\Delta y$	grid size in the y direction.
$a$	a constant, equal to 0.5 when salinity is in units of ppt
$A$	cross-sectional area through which the water flows [ $m^2$ ]
$A_n$	average annual precipitation in year n
$A_o$	average historical annual precipitation
$A_{c,I}^t$	land area in cell I, allocated to crop c, for year t
$A_{c,I}^{t-1}$	land area in cell I, allocated to crop c, for year t
$b$	empirical “farmer rationality” coefficient
$c_I$	constant costs associated with each crop
$C_{Total}^t$	total crop production costs at time t per unit area
$c_w$	cost of water use in litres/Drachma
$d$	day of the year
$d_i$	water requirements of crop c for maximum production
$D_{c,I}$	desired area of land in cell $i$ allocated to crop c
$ET_{crop}$	crop evapo-transpiration rate
$ET_0$	measured evaporation rate
$h$	difference in height [m]
$h_h^0$	level of water in aquifer at time $t = 0$
$h_h^t$	level of water in aquifer at time t
$H_{I,j}$	historical hydraulic head at location i,j;
$h_{I,j}$	modelled hydraulic head at location i,j.
$i$	rainfall intensity
$k_c$	crop coefficient
$K$	hydraulic conductivity [ $m^2s^{-1}$ ]
$l$	distance travelled [m]

$p_i$	perfect rate of production of crop $c$ in kg/ha
$P_{c,i}$	profitability of crop $c$ in cell $i$
$Q_T$	volumetric flow at time $T$
$Q$	volumetric flow of water per unit time [ $\text{m}^3 \text{s}^{-1}$ ]
$r$	random number between 0 and 1
$r$	price paid for the crop (Dr/ha)
$r_s$	resistance to salinity parameter for a given crop
$R$	recharge, volume of inflow to the system per unit volume of aquifer per unit time
$P_a$	actual production (kg/ha)
$P_p$	perfect production (kg/ha)
$R_o$	reduction in production due to soil suitability
$R_s$	reduction in production due to salinity
$R_w$	reduction in production due to water shortage
$S$	supply of water in cell $z$
$S_c$	salinity concentration in ppt
$S_s$	specific storage, the volume of water released from storage per unit change in head ( $h$ ) per unit volume of aquifer
$T_d$	daily temperature
$V$	demand for water in cell $z$

## CHAPTER 1: INTRODUCTION

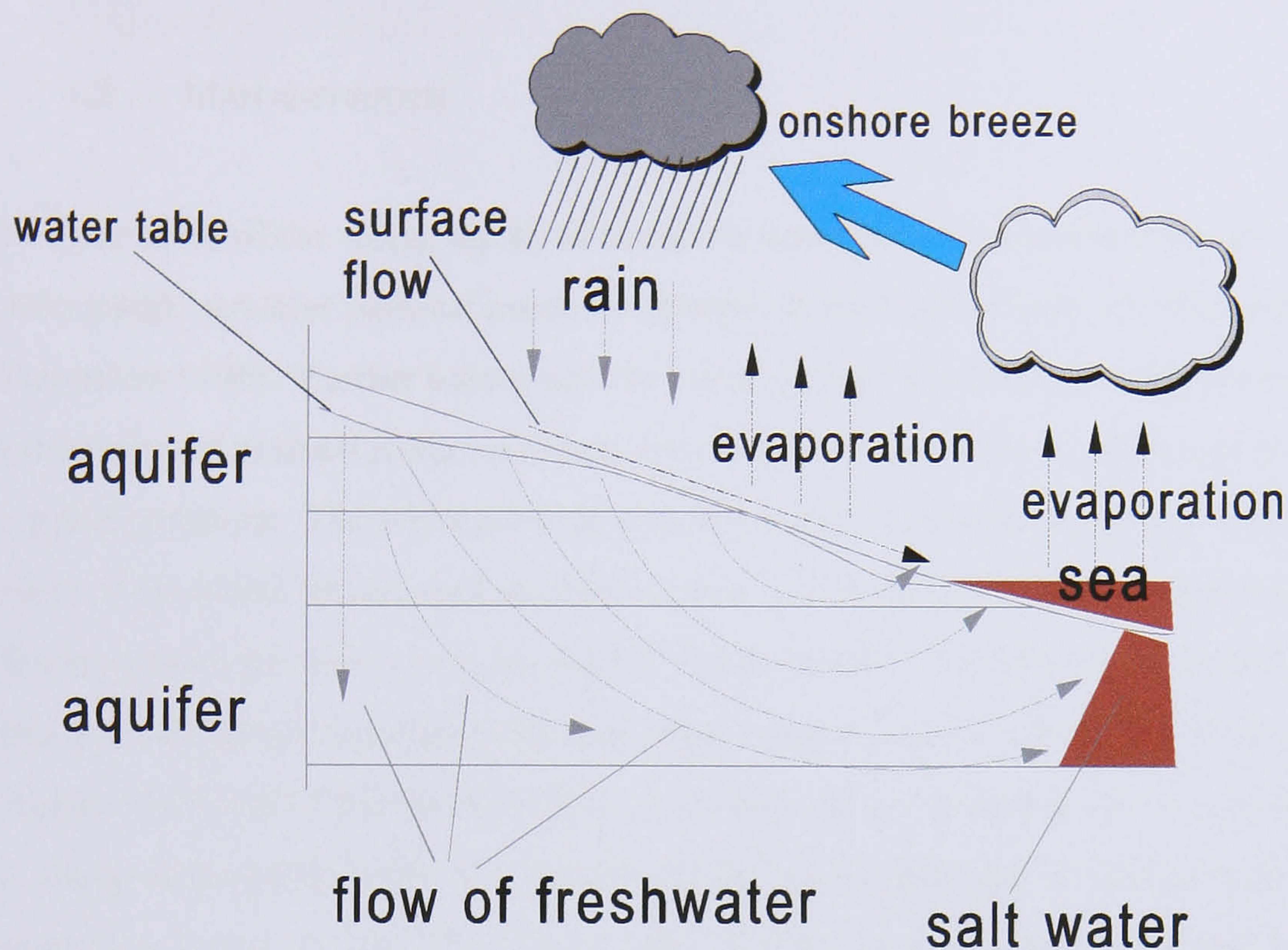
Denied water, a human being will die within a week. It is clear that water is a resource that is vital to humanity and is the most vital ingredient for human life (Jones, 1997, p.2). Water is required for almost all forms of agriculture, and historically the growth of many civilisations was influenced (if not controlled) by their access and ability to utilise water (Newson, 1997). Yet, because of its ubiquity water is a resource prone to numerous competing demands. As environments become increasingly human dominated, so humanity's use of water has become the dominant factor controlling the volumes, flows and quality of fresh water. Complex laws and rules have been formulated to control the use of and access to water both as a supply for use and as a receptacle for waste.

Water covers approximately 70% of the surface of the Earth. 97.4% of the water on the Earth is in the oceans and is too saline to be used directly for human consumption or agriculture (Merrett, 1997, p.5). The remaining 2.6% of the total water mass is fresh water. However 85.9% of this fresh water (2% of the total) is trapped in the polar ice caps. Groundwater comprises a further 13.5% of fresh water, leaving only 0.6% of freshwater in rivers, soils and the atmosphere. Therefore, it is obvious that exploitation of groundwater has the potential to vastly expand the amount of freshwater that is available to be used by humanity.

### 1.1. THE HYDROLOGICAL CYCLE.

The hydrological cycle is the term used to describe the set of processes that transport water around the globe. Figure 1.1 shows the basic form of the cycle. Seawater is evaporated from the ocean by solar heating, and is retained in the atmosphere as (fresh) water vapour or microscopic droplets (clouds). The temperature differential between land and ocean causes advection of the air towards the land. Because the land is higher, the air is forced to rise, cooling the air. Cold air can retain less moisture and excess moisture is precipitated from the atmosphere onto the land. After being precipitated, gravity causes the water to flow downhill across the surface of the land. During this





**Figure 1.1 The hydrological cycle.**

surface flow, the water collects into rivers and lakes, percolates into the soil and rock, and is evaporated back into the atmosphere either directly from the land surface or after being taken up by plants (transpiration). It is only during this part of the hydrologic cycle that fresh water is available to be used by man.

There are several important factors that affect the hydrologic cycle. The topography of the land strongly affects where precipitation occurs, so that high levels of precipitation may be expected on the windward side of high ground. *Vice versa*, low levels of precipitation may be expected on the leeward side, an affect commonly known as a Arain shadow≡. The latitude of the location also has a strong effect, due to the variation with latitude in solar energy incident upon the Earth's surface. The variation in incident solar energy affects air temperature and sea surface temperature, both of which control the evaporation rate from the sea surface. Finally, the climate, especially in terms of winds and ocean currents, plays a strong role in the distribution of atmospheric moisture and precipitation. Thus, it can be seen that the hydrologic cycle represents an important link between a location and the rest of the global climate.



## 1.2. MAN AND WATER

In many areas of the world, equity of access to water resources is becoming an increasingly sensitive political issue, for example in the Middle East (The Economist, 23 December 1995). Further issues, such as water pricing, are also increasingly entering the economic and political arenas as means are sought to control the use of water in an equitable manner. There is a growing awareness that the level of water use on large parts of the planet has reached saturation point, i.e. the level of use is so high that small fluctuations in the water cycle can lead to "catastrophes". Notable recent examples of this in Great Britain were the water shortages in Leeds and Bradford (The Economist, 15 August 1995 and 18 November 1995). A combination of localised very low rainfall and a change in the public attitude to appeals by the newly privatised Yorkshire Water for reductions in use, resulted in a drastic water shortage and the transport by road of water to the afflicted regions. The (lack of) response of the public to these water shortages, and appeals for reduction in water use has been attributed to the change in the status of the local water supplier from being a publicly owned utility to being a privately owned and highly profitable company (Heathcote, *pers. comm.*). This example provides a graphic demonstration of the complex nature of water resource problems, where apparently small changes in any one part of the system can drastically reduce the viability of the system in the face of natural environmental variation. It also demonstrates how small changes in different parts of a system can combine to cause large overall changes in the behaviour of the whole system and that the behaviour of humanity can be a crucial factor to consider.

One of the most fundamental problems with water use by man, is its treatment as a common and unlimited resource. For most of human history, the level of use of water has been far lower than the available natural supply. In this situation, there is no incentive to restrict water use, though legal codes in different societies have evolved to try and prevent anti-social abuse of water resources (Caponera, 1992, Chapter 13). However, legal restrictions regarding water have normally developed as a result of abuse

occurring in the first place, in other words the evolution of laws have followed events rather than leading them (e.g. the law relating to extraction licenses in the U.K.). The treatment of water as a common and unlimited resource is only sensible when and if the level of human use is much lower than the natural availability of water. As the global population has grown it has become increasingly rare for this criterion to be met. In addition, variations in climate, whether natural or man-made, can exacerbate the situation when the natural availability of water is reduced.

### 1.3. A COMPLEX SYSTEMS APPROACH TO MODELLING WATER RESOURCES.

The environment in general, and water resources in particular, are archetypal examples of complex systems. A complex system may be defined as a system that has evolved a hierarchy of functional structure (Clark et al., 1995, p. 36) consisting of numerous sub-systems connected by a wide variety of (non-linear) processes. For water resources, the interaction between the numerous systems that are related to water resources (topography, geology, soils, weather, vegetation etc), comprise an intractable problem for the traditional, reductionist scientific approach to investigating problems. Efforts to circumvent this intractability have resulted in a disciplinary approach to water resources, whereby each scientific discipline tends to only consider water resources problems from the perspective of their own discipline. Thus, for example, an economist and a hydrologist could both study the construction of a new canal, using the Cost Benefit Analysis (Merrett, 1997, p.85 *et seq.*; Hardwick *et al.*, 1982) and numerical modelling (Gupta, 1996) as their respective tools. The only intersection between the questions they may ask (e.g. “Will the canal be profitable?”, “Will it supply enough water?”) and therefore the answers they arrive at will be in the context of the situation. Neither can (nor attempts to) say anything about the broader picture, which extends beyond the bounds of any one discipline. This pattern of research can be called a disciplinary approach.

Whereas, a disciplinary approach starts with an automatically constrained system, the complex systems approach by contrast, starts with a more or less unbounded system. By



characterising a problem as occurring within a complex system, automatically the interactions between the various component sub-systems must be considered. The first step is to identify the parts of the structure of sub-systems, which are important to the particular problem, and to then place suitable bounds around the system. Then the processes and variables that are found within these bounds are identified. The next stage is crucial, when only those variables and processes that can be said to be unimportant to the particular problem (causal relation) being investigated are removed from the system definition (description). When the system has been reduced to only those parts that are considered vital, then the process of model development can begin, based upon this description. In this research, I will be applying these principles to the environmental problems that have developed in a particular location in southern Greece, the Argolid valley.

#### 1.4. A HISTORICAL PERSPECTIVE ON THE SITUATION IN THE ARGOLID VALLEY, GREECE.

The Argolid valley is a semi-arid coastal valley in the Peloponnese peninsula of Greece (see Figure 1.2), consisting of a plain with clay soils surrounded by mountainous karstic terrain. The population is just under 50,000 and has remained at this level since the 1940's. The largest town, Argos, is located on the western side of the plain. The main industry is agriculture, which is restricted to the plain and foothills (approximately below the 200-m. a.s.l. contour, see Figure 1.3). Following the introduction of subsidies in the 1950's, irrigated citrus crops have increasingly dominated agriculture in the valley.

Traditionally, irrigation water has been supplied from boreholes sunk into a sandy aquifer(s) underlying the plain. These boreholes were augmented in the late 1960's by a small canal bringing water from a small freshwater spring (Kefalari), in the foothills of the Artemisian Mountains. This was further augmented by a much larger canal, built in the late 1980's and early 1990's which uses the coastal springs at Anavolos for its supply.

Though the Anavolos spring has much greater and more constant volumetric flow than Kefalari spring, it is slightly brackish. At present, in winter, the water from Kefalari spring is mixed with the water from Anavolos to reduce its salinity, and the mixture is being used for artificial recharge of the aquifer beneath the plain. Both springs are fed





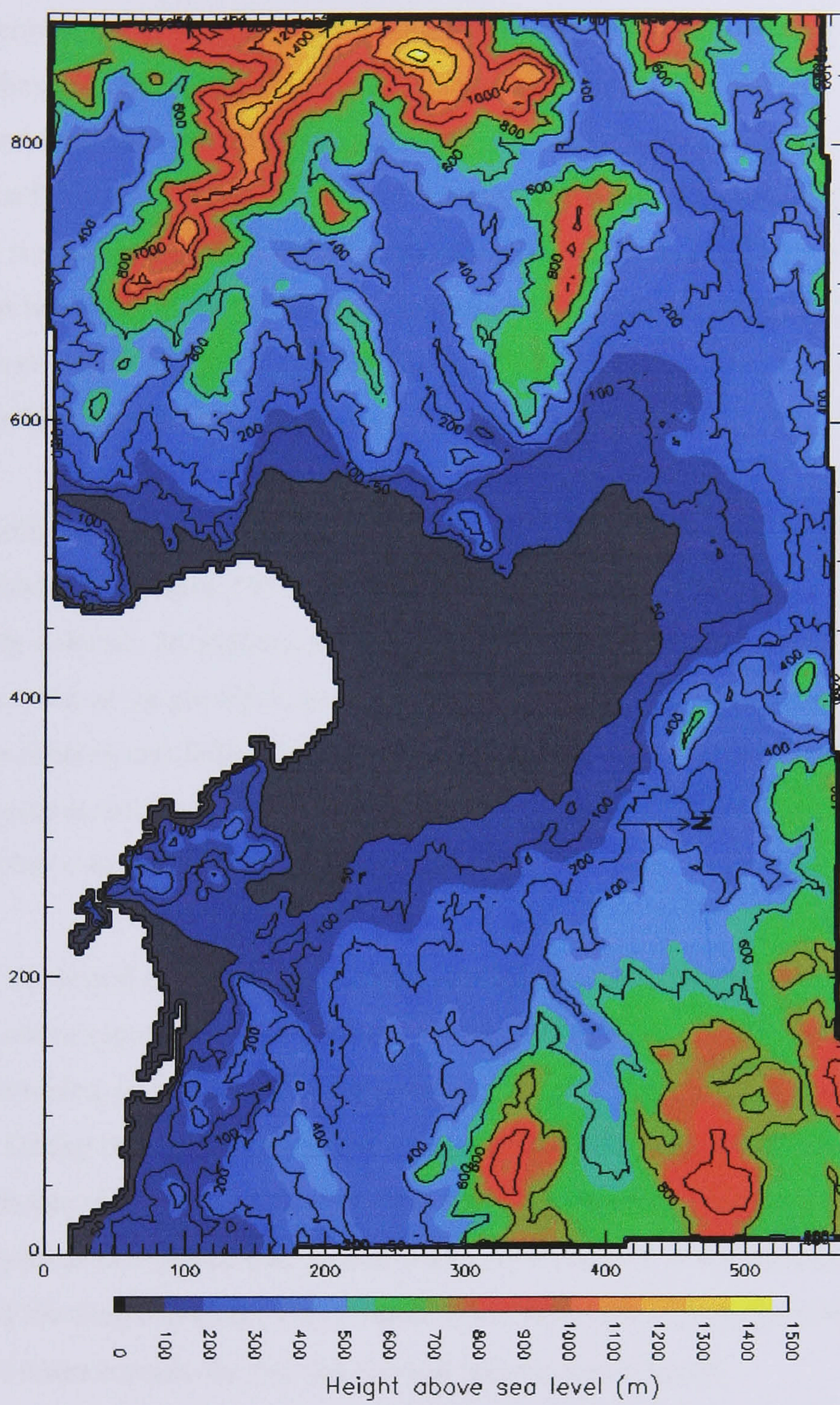
**Figure 1.2 The location of the Argolid valley, Greece (indicated by red box).**

from areas outside of the catchment area, by channels through the limestone (typical of karstic terrain) so the creation of the canal(s) represents an expansion in size of the catchment area feeding the Argolid valley.

In the early 1990's it became apparent (Poulovassilis et al., 1994) that serious environmental problems were developing. Consecutive years of reduced rainfall on the plain had placed an increasing demand upon groundwater for irrigation use, and boreholes began to fail either through absence of water, or through excessive salination. Prolonged use of salinated water from the aquifer for irrigation was also beginning to have an impact upon soil quality and crop yields. The government response has been to build canals to bring water from springs at the foot of the karstic mountains to the main citrus growing areas in the central plain.



Figure 1.3 Topography of the Argolid Valley, Greece (Hellenic Army Series, 1977), contour heights are in metres.





This canal water has been used for both irrigation purposes and (more importantly for the long-term future of the valley) for artificial recharge of the aquifer in winter. The latter will have the effect of increasing the resilience of agriculture within the valley to climatic variability, and should eventually restore the quantity of water within the aquifer to (presumed) historical levels. Because this spring water has a relatively high salt content, it is possible that there will be a long-term decline in the quality of the ground water. This has implications for the crops that can be grown in the valley, and whether agriculture remains a viable industry for the Argolid in the longer term. Combined with normal rainfall levels, the artificial recharge has restored water levels within the aquifer.

More recently, as the European Union has reduced the level of price support for citrus crops (Hubbard and Ritson, 1997), the economic viability of irrigated citrus crops has been greatly reduced. In addition, social changes have occurred in the valley in the last forty years, such as the growth in the number of people for whom farming is a secondary occupation (Lemon and Jeffrey, 1996; Allen et al., 1995). These changes in the socio-economic system have reduced the adaptability in the pattern of agricultural practices since the 1960's, for both social and economic reasons.

Following the period of drought on the plain, severe flooding occurred particularly near the coast, where topographic gradients are very small. The cause was identified (Giannouloupoulos, *pers. comm.*) as being a large reduction in the number of drainage channels. During the drought, the farmers had not maintained these channels, allowing them to become blocked by debris and vegetation. Because the land near the coast was very low-lying (and in places was drained marsh) when rainfall levels returned to normal widespread flooding occurred. This resulted in the destruction (by suffocation) of large numbers of citrus trees as the soil and sub-soil became waterlogged.

Other problems that have occurred in the valley are related to the pattern of agriculture that has developed in the central plain, which now approaches monocropping. This allows diseases to spread rapidly through the crops, causing catastrophic damage. The initial irrigated crops were apricot trees, however an outbreak of Sharka virus led to all

the trees being uprooted and replaced primarily by orange trees (Allen et al, 1995). Because of government aid to the farmers this was not a catastrophe in economic terms for individual farmers.

However, the fact remains that the farmers are now economically dependent (to maintain their current standard of living) on a subsidised, irrigated crop in a semi-arid area. Thus, the construction of canals and recharging of the aquifer have only been successful in treating the symptoms of the true problem, this being the predominance of a type of agriculture that is inappropriate for the climatic conditions.

The problem is therefore to change the way the environmental resources (i.e. water) are being exploited, while at the same time maintaining the farmers' incomes, since it is politically impossible to propose a solution which would reduce the farmers' incomes. We are in fact dealing with what may be classified as the interactions between two very different systems, one physical and one socio-economic. The first step to solving this problem is to understand the nature of the interaction, and then use this understanding to try to produce quantitative answers.

#### 1.5. THE WATER RESOURCE SYSTEM.

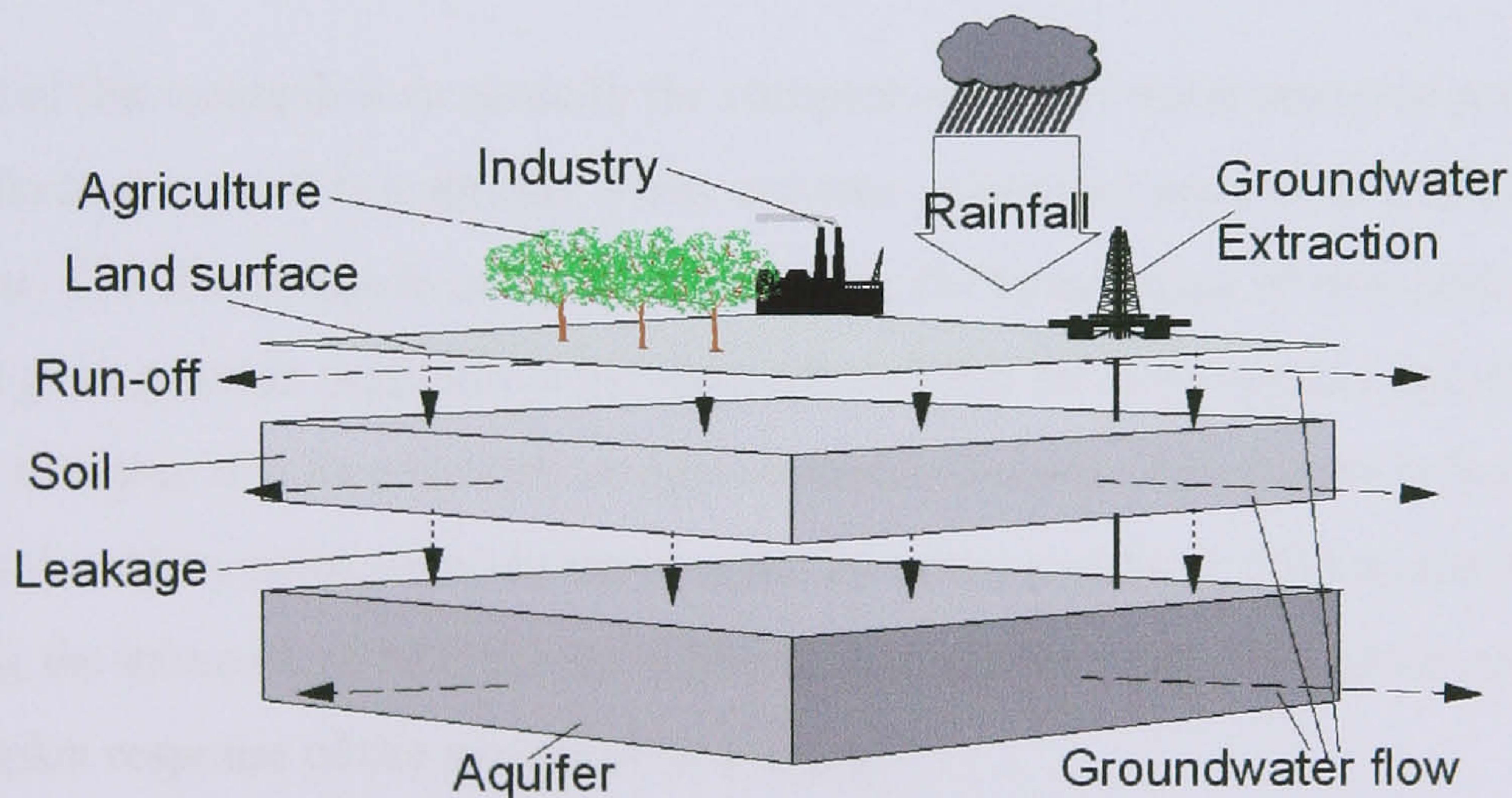
Having described the situation that has developed in the Argolid Valley, it is now necessary to define the water resource system for an area such as the Argolid valley, using a complex systems approach. This requires that all other systems, which are directly related to water in the environment, should also be considered before being included or excluded from the definition of the water resource system.

The water resource system in its most basic form consists of all sources and potential sources of water within a given system, and normally falls within the domain of the hydrological and hydrogeological sciences. However, while this system has its own internal dynamics (basically driven by the force of gravity), it is essentially a passive



system, only responding to the effects of other systems upon it, be they climatic, geological or economic systems. Indeed, water resources could be considered to be the physical connection between these different systems, through the process of the hydrological cycle, rather than being a separate system.

Since other systems essentially drive the dynamics of water flow, it is necessary to include these other systems and their relation to water resources in any attempt to understand in detail how problems with water resources can lead to problems that are more widespread (extend to other systems). Thus I define the water resource system as being not only the quantities and qualities of water on and below the ground, but also the physical domain in which that water exists, and the economy which uses water and physically resides upon the land surface. Figure 1.4 gives a conceptual picture of this system.



**Figure 1.4 The water resource system.**



However, because the processes that compose other related systems operate at a range of different temporal and physical scales, each process must be considered separately, to decide if it should and can be included in a numerical model of the water resource system.

#### 1.6. THE AIM OF THIS RESEARCH.

The problems in the Argolid valley are highly complex, involving the interaction of numerous different systems. Further, the environment in the Argolid may be described as being human-dominated (Vitousek et al., 1997), in that the activities of the human population is the primary source of local environmental change. The Argolid represents a particularly good location to study the interaction between human and environmental systems because of the relative simplicity of the economic system and the use of water. There is a lack of regulation on the use of ground water for agriculture and irrigation techniques are a mixture of primitive (flood or free-flow irrigation) and more advanced systems (sprinkler or “artificial rain” irrigation). In addition, the coastal location and the characteristics of the local geology mean that water resource problems can develop quickly.

The aim of this research is to quantify the complex causes of water resource problems, and to illuminate possible solutions. There are two points that need to be addressed in particular. The first is that in order to be useful for the formulation of new policies, the research must provide quantitative information, and that this information should be reliable, or rather that its reliability be approximately known. The second is that the research should try to incorporate the complexity of the problems. This means that by including the interactions between the different systems the research reproduces (models) the complex response of the system(s) as a whole.

The only successful approach to studying the problem is therefore to integrate both the physical system and the social system. Allen et al. (1995) documents a study of the

problems of the Argolid, in which an integrated approach is taken to study the interaction between agriculture and water resources. This culminates in the development of a numerical model that includes both the hydrological system and the economic system. The model is rather simple, consisting of only seven geographical zones, and is restricted to the central plain, where agriculture takes place. Furthermore, the geographical structure is incorporated directly into the model structure, making it very difficult to apply the model to other locations. The hydrogeological system is treated in a very approximate way, with no flow equations as such. Flows between zones and into the model from the surrounding hills are specified so that conditions in the aquifer evolve in a way that corresponds to the historical development of the Argolid. The economic system is represented by an econometric description of the allocation of cultivated area to different crop types, as a representation of the behaviour of farmers in the valley.

The main limitation with the model of Allen et al. (1995) lies in the hydrogeological system, which does not include the natural dynamics of the aquifer, and the behaviour of which has been largely specified. An improved approach would be to have a dynamic hydrogeological system, with physical parameters based upon the physical characteristics of the environmental system in the Argolid, which can freely interact with the economic system. This indicates that a quantitative, numerical model should be used to reproduce the behaviour of the water resource system and its interaction with the economy, and in particular with agriculture. The model should include all parts of the general environment that are directly related to the water resource system, and reproduce the overall behaviour of agriculture in the Argolid. Therefore, the aim of the research is to produce a quantitative, numerical, systemic model of water resources and agriculture, and apply this model to the Argolid valley.



## **CHAPTER 2: REVIEW OF APPROACHES TO THE STUDY OF ENVIRONMENTAL PROBLEMS.**

Chapter 1 introduced water resources, discussed the problems that have arisen in the Argolid Valley, and concluded that a numerical model integrating water resources and the farmer's behaviour was the best method of studying the situation. This chapter will review the literature regarding environmental problems, in particular water resources, and define the context for the results of this research in this thesis.

### **2.1. INTEGRATED SYSTEMS MODELS.**

Literature regarding numerical models that integrate systems normally considered to be part of separate scientific disciplines is limited. What tends to happen is that each discipline develops its own model(s) and then the models, which are regarded as most successful within their own discipline, are linked together. While this has the advantage of not requiring additional model development beyond that involved in connecting the two models, it does not fully consider the appropriateness of the resulting combined model.

An example may be taken from climate studies. Meteorologists and oceanographers have both developed general circulation models for their respective domains (e.g. Webb et al., 1997), which are driven by essentially the same set of equations (the Navier-Stokes equations for fluid flow) and which include parameterisations of external influences. In the case of both disciplines, the models have proved to be very successful. However in order to study the climate as a whole, it is necessary to model both atmosphere and ocean together, resulting in a coupled ocean-atmosphere general circulation model (Manabe and Stouffer, 1994; Cane & Zebiak, 1987). The use of these models has highlighted the problems inherent in modelling the interaction between two systems. The interface between the two systems is powered by solar radiation, and because both models only parameterise this radiative forcing, the performance of combined models does not match the performance of the component models.

More appropriate methods of studying the climate as a whole are to design a model for that purpose, using only an appropriate level of complexity (Ganopolski et al., 1998), to model the crucial aspects of the interface between the atmosphere and ocean explicitly, or to limit the application of a combined model to a domain where the parameterisation of the interface is appropriate (Bush and Philander, 1998).

However, the above examples are both purely physical as opposed to social systems. Almost by definition the natural sciences lack the tools to handle human behaviour. Furthermore, the culture which characterises the natural sciences (or rather scientists) recoils from any attempt to include human behaviour, because the inclusion of independent actors capable of making decisions contravenes the principle of reproducibility, i.e. a person can change their mind for other than rational, logical reasons which therefore renders useless the forms of inquiry used by the natural sciences.

*Vice versa*, attempts to extend social sciences (e.g. economics) to include the interaction between man and the physical environment (such as Redclift, 1985) are doomed to failure since the social sciences lack the framework of knowledge about the environment which would enable an objective understanding of this interaction

## 2.2. DIFFERENT APPROACHES TO THE ENVIRONMENT.

It is relatively easy to separate the environmental literature into two separate parts. These parts are not defined by scientific discipline, but rather by the style of approach, and may be described as quantitative and qualitative (or predictive and descriptive).

### 2.2.1. *Quantitative approaches.*

The complexity of the environment is such that quantitative approaches to the study of environmental problems are almost exclusively discipline-specific. That is to say that they are only concerned with the environment from the point of view of the relevant



discipline. Given the problems that have occurred in the Argolid Valley (Laboratory of Agricultural Hydraulics, 1993), this review is restricted to the those disciplines that seem most relevant.

### **Hydrology/Hydrogeology**

The study of the flow of water above and below ground is an old occupation. Xenophanes of Colophon (570-470 BC) stated that “the sea in the source of the waters and the source of the winds, without the great sea, not from the clouds could come the rivers or the heaven’s rain” (Newson, 1997), which is an approximate description of the hydrological cycle. Because of this long history, it has (and still is) an essentially empirical science.

Numerous empirical methods have been developed to describe mathematically the behaviour of water flowing on and below the land surface. The most basic description of the flow of water below the ground, Darcy’s Law, is essentially empirical (Domenico and Schwartz, 1998, p.33). It specified a new physical parameter, hydraulic conductivity, which can often only be measured (rather than predicted), as it combines properties of both the physical material composing the rock, and the micro and macroscopic structure of the rock.

Equally, above ground the hydrograph is a description of the temporal history of the rate of flow from a catchment following a rainfall event (Shaw, 1994, p.319). This evolved into a series of empirical relations which essentially predict the flow of water from different parts of a catchment, but which again contains physical parameters which are defined by comparison with data from the catchment.

These empirical methods are essentially macroscopic parameterisations of numerous microscopic processes, which are too complex to be modelled as a whole at present. However, attempts are being made to produce models of this complex behaviour (Allen et al, 1997), but again there arises the question of appropriate level of resolution



(definition) with respect to processes which are appropriate to include in the model.

## Economics

Economics may be defined, as the scientific study of the allocation of scarce resources, which have alternative uses, to the satisfaction of competing wants (Maile, 1983, p.9, Heal, 1993, p.xi). As such it is dealing with the behaviour of statistically large numbers of people, and how they interact with each other and the various structures forming (economic) society. When dealing with the environment however, economics runs into difficulty. A requirement of economics is the allocation of values to all goods.

This leads to the “tragedy of the commons” (Hardin, 1968) where the lack of value of a resource leads to the inefficient use of it, or more precisely until it is no longer profitable to use it. In addition, ground water (in the Argolid) is a free *good*, which means that there are no costs associated with it. Economic theory (Hardwick et al., 1982, p.86) states that a free good is one where a fixed supply is far greater than demand, for all possible demands. This was the historical situation in the Argolid, where the technological limitations of wind and animal powered pumps limited abstraction of groundwater. If we take the supply in this case to be the *safe yield*, defined as the maximum sustainable abstraction rate (Domenico and Schwartz, 1998, p.137), then the situation becomes further complicated by negative feedback. When the demand expands (through improved technology and the desire to grow new crops) to be greater than supply, this has the effect of further reducing the supply. Thus, not only does the *free* nature of ground water allow inefficient use of it as a resource, it further indicates that at some point in time, rising demand will cause a decline in the available supply. Due to natural temporal variability in the supply, this may occur before demand has reached a calculated *safe yield*, as has been identified in other natural systems (Allen and McGlade, 1987).

Furthermore, reductions in the quantity of available ground water are often associated with reductions in quality, as pollutants become concentrated in decreasing volumes of



water. Therefore, in economic terms, ground water can be both a renewable resource and (potentially) an exhaustible resource. This represents an intractable problem for economists since there are two distinct regimes. If the ground water resource is well managed (or under used) then it is essentially *free*. However, once demand approaches or exceeds supply, both the quantity and the quality of the supply reduce, thus reducing the profitability of the activity.

The “tragedy of the commons”, also explains why farmers have not invested in more efficient forms of irrigation (Gravelle and Rees, 1981, p.515). Because investment in new technology allowing farmers to use less water for a given amount of crop production will have a cost, but saving water does not reduce costs and therefore the farmers have no incentive to invest. If a farmer does invest in new technology then the benefits will accrue to all farmers using the aquifer.

#### 2.2.2. *Qualitative.*

This approach may be characterised by an attempt to describe the environment within an integrative framework, that attempts to capture the complexity and evolutionary nature of many environmental processes. A typical example is “Geoecology” (Huggett, 1995), where the evolution of the landscape is approached from the perspective of an ecology of processes. This is a very rich approach in that it is inclusive of all environmental processes that can influence the evolution of landscape, operating at different temporal and spatial scales. It is based upon the field of landscape or geo- ecology (Troll, 1971, 1972) which is concerned with the causes and effects of spatial heterogeneity in ecosystems. Therefore, it considers processes that operate at a wide range of spatial and temporal scales to generate heterogeneity within apparently stable, homogenous communities.

One of the most enlightened facets of geoecology is the appreciation of the effects of scale. To quote from Huggett (1995, p.17):

*the results of an investigation of a geo-ecosystem will be influenced by the*



*scale chosen to study the patterns and processes.*

This may seem to be an obvious comment, but the effects of scale are often studiously ignored, particularly by the quantitative approach, either because of an assumption of scale independence, or for simplicity (or both).

### 2.3. DIFFERENT APPROACHES TO MODELLING ENVIRONMENTAL PROBLEMS.

It was mentioned in Chapter 1, that one of the important distinctions of the complex systems approach is the initial "holistic" view of the systems in question. This specifically includes the interaction of different parts of the system parts. The discipline specific view of model (or problem) definition, where each discipline defines a given problem in terms of its own points of reference, may be considered to be a subset of the complex systems approach outlined above. The complex systems approach starts with the whole system (environment) and removes parts of the system which are not considered essential, so in the case where the system is reduced to parts which fall within the purview of one discipline, the result is the same as the discipline specific approach.

#### 2.3.1. *Critique of the approach of hydro(geo)logical models.*

Hydrogeological models such as MODFLOW (McDonald and Harbaugh, 1988) and AQUIFEM (Wilson et al., 1979) are based upon the same physical laws as the Aquifer sub-model described in Chapter 4. They have very specific and often highly detailed data requirements and are designed for purposes such as small-scale geological and civil engineering problems such as contaminant dispersion (e.g. Fortina et al., 1993) (for which purpose they were originally created), or infrastructure design and operation, where there is a requirement for a high degree of numerical precision (Anderson and Woessner, 1992, p.2). However these characteristics, and in particular the data



requirements, mean that it is quite cumbersome to apply the models to situations where the interaction with other systems is a crucial part of the problem being studied. In particular, though these models may be able to reproduce the dynamics of the hydrogeological system, other systems may only be represented indirectly. This will make prediction using the model particularly difficult, because of uncertainty in the future values of static parameters (Anderson and Woessner, 1992, p.259). Further problems may result from scaling effects between the model domain and unmodelled heterogeneity in the field measurements upon which the model domain is based (Anderson and Woessner, 1992, p.229).

To summarise, hydrogeological models are designed for a specific, narrowly defined, purpose. That is to model water heads, flows and the associated solute transport, with a high degree of precision and often on a comparatively small scale. This requires a large amount of data, and by necessity the models are restricted in terms of their internal dynamics to the hydrogeological system. They are thus ill suited to consider situations where the interaction between the hydrogeological system and other parts of the environment are important.

Indeed, the original intention for this project was to use part of MODFLOW, a model which is both published and publicly available (McDonald and Harbaugh, 1988), as the core of the aquifer sub-model. However for the above reasons, it became apparent that a model with the same mathematical basis, but specifically (numerically) designed to interact with other systems would be more valuable in the long run, because of the greater flexibility in investigating the dynamics of the interaction with other sub-systems.

### 2.3.2. *Econometric modelling.*

Rather than develop a separate model of the economy in this research, the intention is to use the econometric model of Allen et al. (1995, Chapter 10) to reproduce farmer behaviour regarding crop selection and water use. This is a model of the way farmers allocate land to different crops. The cost and availability of water, together with the



quality of the soil and the price of each crop, affects the choice of crop(s) and the allocation of land between the different crop types, and does not affect short term water decisions (Moore, 1994). Once land has been allocated to each different crop (which happens annually), farmers will attempt to meet the water requirements of their crops on a daily basis. Thus the daily pattern of water use varies solely according to the relative balance between evaporation and precipitation. Because the trade-offs between production losses due to water shortfalls are highly crop dependent, and will vary significantly even between different varieties of the same crop (FAO, 1987), the parameters used within the econometric model are only approximate. Even though there is no pricing mechanism for water in the Argolid, the model uses an effective water price to simulate the ease (difficulty) in obtaining water and this price then modifies the crop choice/land allocation decisions of the farmers.

It is also worth considering the literature regarding the economic viability of water resource infrastructure projects, since canals have been built in the Argolid and it appears doubtful that agriculture in the region is profitable enough to even fund the long term maintenance costs of these structures (Allen, pers. com.).

Cost-benefit analysis applied using linear programming is used in Haines and Kindler (1981) and in Loucks et al. (1981) to decide on the value of water resource projects. Similar methods are discussed in Mergos (1987) which uses quadratic programming and emphasises the importance of uncertainty in affecting whether irrigation projects achieve their aims. More recently Merrett (1997) discusses social cost-benefit analysis/social cost-effectiveness analysis, using the particular example of the use of a simulation model in Peru, to demonstrate the problems with social cost-benefit analysis (Merrett, 1997, p.100-106). The cost-benefit analysis approach has the disadvantage that it treats both the physical and the economic systems in a deterministic way, so that there is no flexibility or evolution in the economic system.

Furthermore, the common assumption in all of the above is that there exists some agency which has responsibility for water resources. To quote from Loucks et al (1981), page



506:

*Those who develop regional water quality models usually assume the actual or potential existence of some governmental institution that has the authority to control water quality within its region, either by economic incentives such as effluent charges and/or by legal means such as effluent standards.*

Effectively, this is the situation in the Argolid regarding ground water.

## 2.4. SUMMARY

There is an extensive literature describing water resources and various methods of study from the physical (hydrological/hydrogeological) perspective. There is also an extensive literature relating to the economics of human-dominated (and often man-made) water resources. However, both sets of literature either ignore the other perspective, or treat it in a very simplistic way.

Thus, there is a gap in the literature relating to the interaction between humanity and the environment. In order to make policy relevant predictions about alternate development paths, the interaction must be quantified. Most of the literature dealing with complex integrated systems is largely descriptive.

As indicated in Chapter 1, a numerical model will be used to study the interaction between water resources and the economy. In line with recent thinking in numerical modelling, the numerical model will be developed for the specific scale and resolution (in terms of processes) that are suitable to study this interaction.

A series of research and output objectives for the numerical model can be defined in order to demonstrate the compelling advantages of an integrated systems approach to modelling situations involving the interaction between different systems. The objectives of the model in terms of research are that it should demonstrate that:



- a model designed to model the interaction between different systems is fundamentally different from numerical models of the individual systems;
- an integrated model of different systems has lower data requirements (in terms of precision and density) compared to typical numerical models of the individual systems;
- the model should contain different sub-models, representing the different component systems, which interact dynamically to reproduce the behaviour of the integrated system;
- the model should be generic (geographical datasets are exogenous to the model code) enabling both the comparison of the models performance between different geographical areas and the rapid integration of new data into the model as it becomes available.

These research objectives then define that the output from the model should:

- reproduce the historical evolution of the integrated systems the model represents (model validation) i.e. water resources and agriculture in the Argolid;
- be numerically stable over a wide range of model parameters, even when these parameters are “unrealistic” (model calibration);
- produce results that can be easily analysed to indicate the effects of different policies upon the integrated systems (model utilisation).

The achievement of these objectives will indicate the usefulness of integrated systems models as a tool for investigating policy options.



## **CHAPTER 3: THE WATER RESOURCE SYSTEM IN THE ARGOLID**

This chapter will describe the data that is available to define the domain of a numerical model of the water resource system in the Argolid Valley, as defined in Chapter 1. The domain data is split into three parts, related to geology, atmosphere and economy. The geology represents the physical domain in which the water resource system resides, the atmosphere represents a sink/source of fresh water, and the economy provides the driving, “unnatural” dynamic for water resources in a human-dominated environment.

### **3.1. GEOLOGY AND SOILS**

The geology and pedology of an area form the physical framework in which water resources exist. Furthermore, the macroscopic geological structures define the nature of the topography and in combination with erosive processes control the actual topography of the land surface at any one instant in geologic time. The topography is the primary control on water resources on the land surface (hydrology), while the erosive processes are important in the pedological processes of soil formation. Below the surface, the geologic structures form the macroscopic geometry of the subterranean environment. The microscopic properties of the geology provide the parameters that control the flow of water through the aquifer. In turn the flow of water through the geology modifies both the macroscopic and microscopic properties of the geology (over a geological timescale i.e.  $10^4$  to  $10^9$  years).

Aquifers are geological volumes where fresh water (from the hydrologic cycle) is retained within a porous material. An important characteristic of aquifers, which is particularly relevant to man's use of aquifer water, is the residence time of water within the aquifer. This residence time can vary from years to millennia, and is commonly related to the depth of the aquifer below the surface (the deeper the aquifer the longer time has passed since the water left the hydrologic cycle). In cases where the residence time is significantly longer than the normal (annual) time scale of variation in the hydrological cycle, the water within the aquifer may be described as fossil water and the



extraction of this water may be considered as the mining of a non-renewable resource. Where the residence is quite short, then the aquifer may be considered to be still part of the hydrological cycle, with the aquifer merely representing another water storage body. It should be noted that in several areas of Western Europe, man has effectively altered the residence time of water within the aquifer by the process of artificially extracting from and recharging to the aquifer. In effect the aquifer body has become a sub-surface reservoir in which water is stored for later use. In this situation, the use of the aquifer may increase the sustainability of water use by providing a buffer against the natural climatic variability in the hydrological cycle.

One of the main problems in the Argolid has been land degradation caused by the use of salinated irrigation water taken from the aquifer. Therefore, it is necessary to include the geological and soil systems in the system being studied. Because of the intimate connection between the geology and water resources, it seems appropriate at this point to extend the definition of the water resource system to one that includes the geology (and pedology) as an integral part.

### *3.1.1. Geology*

Figure 3.1 is a geological map of the Argolid valley (Institute for Geology and Subsurface Research, 1970) with topographic contours (Hellenic Army Series, 1977) superimposed. It can be seen that the geology of the Argolid valley is easily divided into different regions. The valley is mainly composed of alluvial sediments deposited in the last 2 million years (Quaternary period). The surrounding mountains are composed of calcitic rocks, mainly limestone, but also dolomites (metamorphosed limestone) with occasional igneous intrusions of ages between 290 (Permian period) and 50 (Eocene epoch of Tertiary period) million years ago. The most recent rocks found are sandstone and sandy marl laid down between 2 and 6 million years ago (Eocene and Pliocene epochs of the Tertiary period). The nature of the geology indicates that the region has undergone significant orographic uplift in the last 2 million years, due to the collision



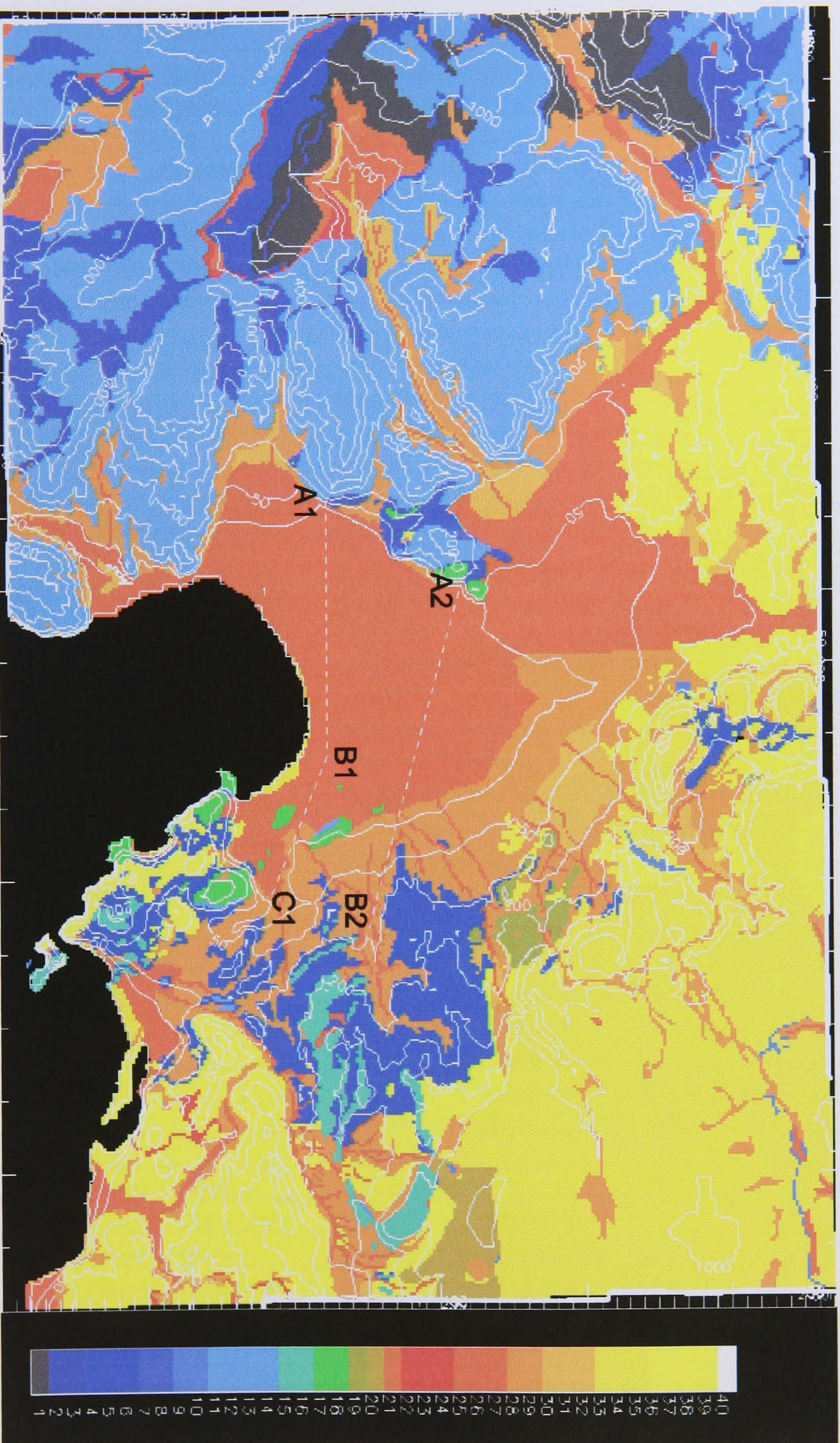


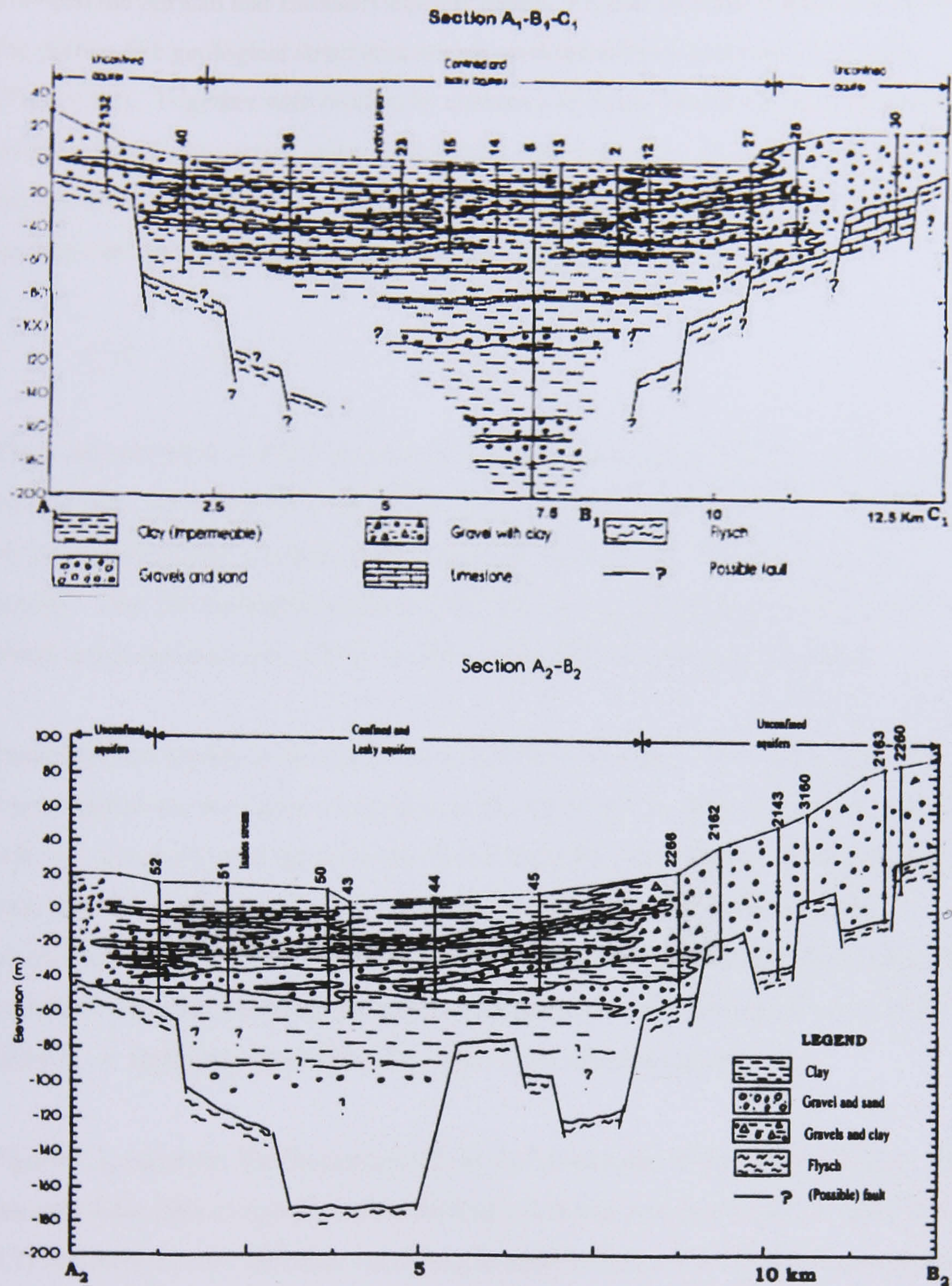
Figure 3.1 Geological map of the Argolid Valley (Institute for Geology and Subsurface Research, 1970) with topographic contours (Hellenic Army Series, 1977). Lines A1-B1-C1 and A2-B2 refer to Figure 3.2. Refer to Table 3.1 (page 24) for key.



Key No.	Geological Sequence	Description of rock type
1	Lower - Middle Eocene	limestones, dolomites
2	Lower - Middle Eocene	flyschoid beds
3	Cretaceous - Eocene	carbonate sediments
4	Maestrichtian - Palaeocene	calcareous shales and marls (flysch)
5	Middle - Upper Eocene	sandstones and sandy marls (flysch)
6	Middle - Upper Eocene	Limestone
7	Maestrichtian - Palaeocene	serpentized eruptive rocks
8	Maestrichtian - Palaeocene	ageritized limestones
9	Middle - Upper Jurassic	Limestones
10	Upper Lias - Upper Jurassic	shale, sandstone chert-formation
11	Upper Jurassic	limestones, dolomites
12	Lower - Middle Jurassic	limestones, dolomites
13	Upper Jurassic	limestones, dolomites
14	Upper Cretaceous (Senonian)	limestones
15	Upper Cretaceous (Turonian)	limestones
16	Upper Cretaceous	limestones
17	Upper Cretaceous (Cenomanian)	limestones
18	Lower Cretaceous - Turonian	limestones
19	Lower Cretaceous - Palaeocene	sediments of the Middle-Manesi group
20	Cretaceous - Middle Eocene	limestones
21	Upper Cretaceous	limestones, dolomites
22	Cretaceous	carbonate sediments
23	Lower - Middle Cretaceous	argillaceous shales, cherts and sandstones
24	Permian - Middle Triassic	keratophyric tuffs, diabases, calcitic sandstones
25	Permian	muscovitic schists, phyllites
26	Quaternary	recent alluvial deposits
27	Quaternary	recent fine alluvial deposits
28	Quaternary	old and recent torrential deposits
29	Quaternary	old and recent alluvial fans and slope debris
30	Quaternary	old cemented conglomerates
31	Quaternary	rock-falls of Eocene limestone
32	Quaternary	recent marine deposits with sand dunes in places
33	Quaternary	coastal marsh deposits, muds and sands
34	Quaternary	aeolian deposits
35	Upper Triassic - Dogger	carbonate rocks
36	Middle Triassic - Upper Lias	predominantly carbonate rocks
37	Middle - Upper Triassic	ammonite bearing limestones
38	Upper Pliocene - Pleistocene	marls, sandy marls and conglomerates
39	Upper Pliocene - Pleistocene	sandy marls, sandstones and conglomerates
40	Upper Pliocene	marine (sandy) marls

**Table 3.1: Key to Figure 3.1. Geological types contained in geological map of the Argolid**





**Figure 3.2 Hydrostratigraphic cross-sections across the Argolid Valley**  
(Poulovassilis et al., 1994, p. 32, 33)



between the African and Eurasian tectonic plates. Further tectonic activity has created the graben-like geological structures seen in geological cross-sections of the valley (Figure 3.2). Together with erosion by streams and rivers caused by the orogenic uplift, this has created the central valley, and filled it with sediment. Thus it can be seen that the topographic and geologic structure found in the Argolid today is the result of geologic processes operating over hundreds of millions of years.

### 3.1.2. *Soils*

There are two ways in which the soil affects the water resource system, one direct and one indirect. All water that is found in a phreatic aquifer has come from the atmosphere, via precipitation onto the land surface, and then percolates through the soil to the aquifer. Thus the vertical hydraulic conductivity of the soil strongly affects the rate at which water can reach the aquifer, which is called the rate of natural recharge.

Indirectly, in a human-dominated ecosystem (Vitousek et al., 1997) and in particular where agriculture is a major component of the economy, the type and quality of the soil will have a major impact upon the use that is made for a given area. For farmers this means that the selection of which crops they choose to plant in a given area is constrained by the suitability of the soil in that area for different crops. Since crops have individual water requirements the choice of crops creates the pattern of water use by farmers. A similar situation arises for other forms of economic activity.

Figure 3.3 shows the distribution of soils in the central part of the Argolid Valley. There are only three distinct (geological) classes of soil in this area (see Figure 3.1 and Table 3.1) but there are five different soil classes in used in Figure 3.3. This indicates that the definition of soil types uses different criteria from the geological classification of the same material. This provides a further example of the difference in approach between scientific disciplines, even ones as close as geology and pedology.



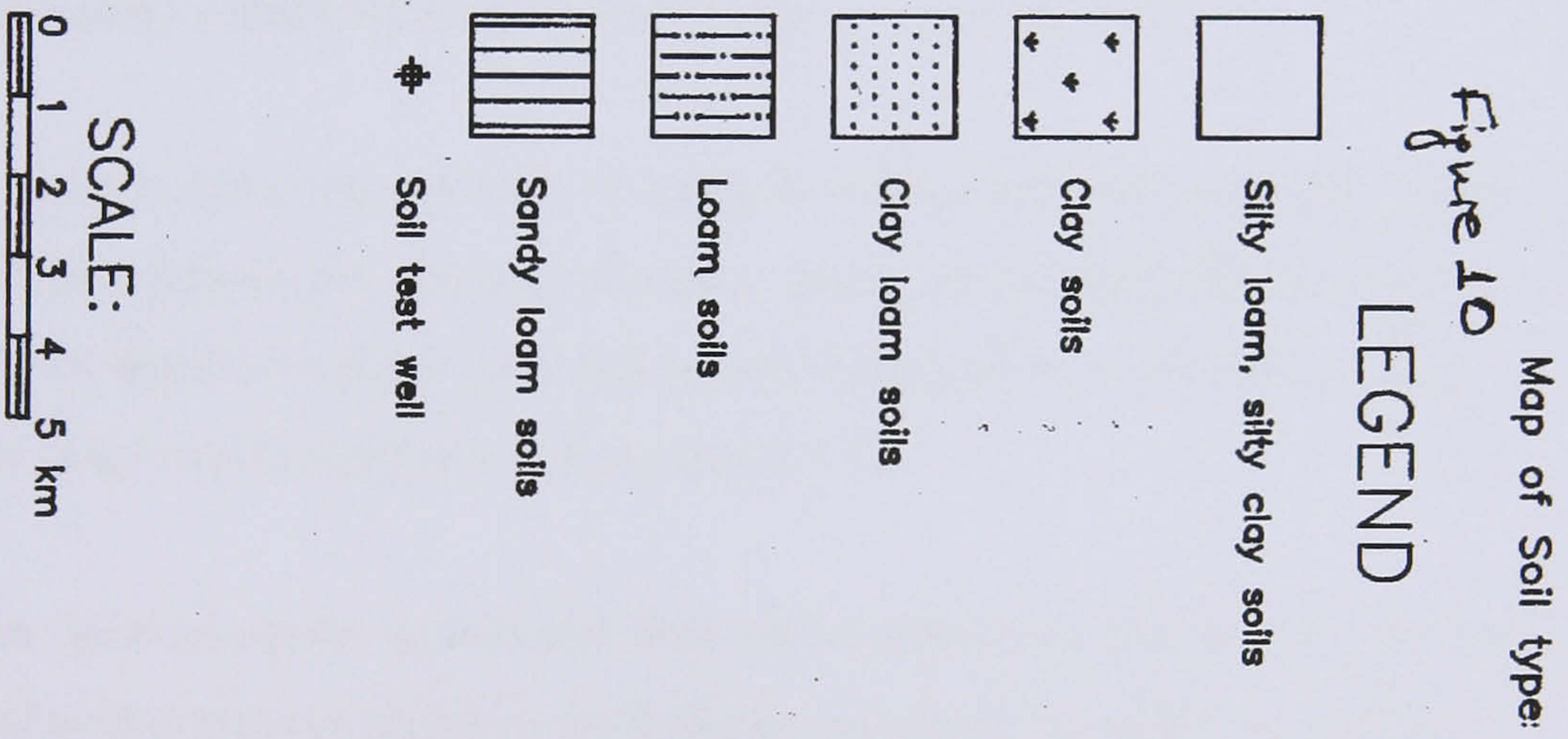
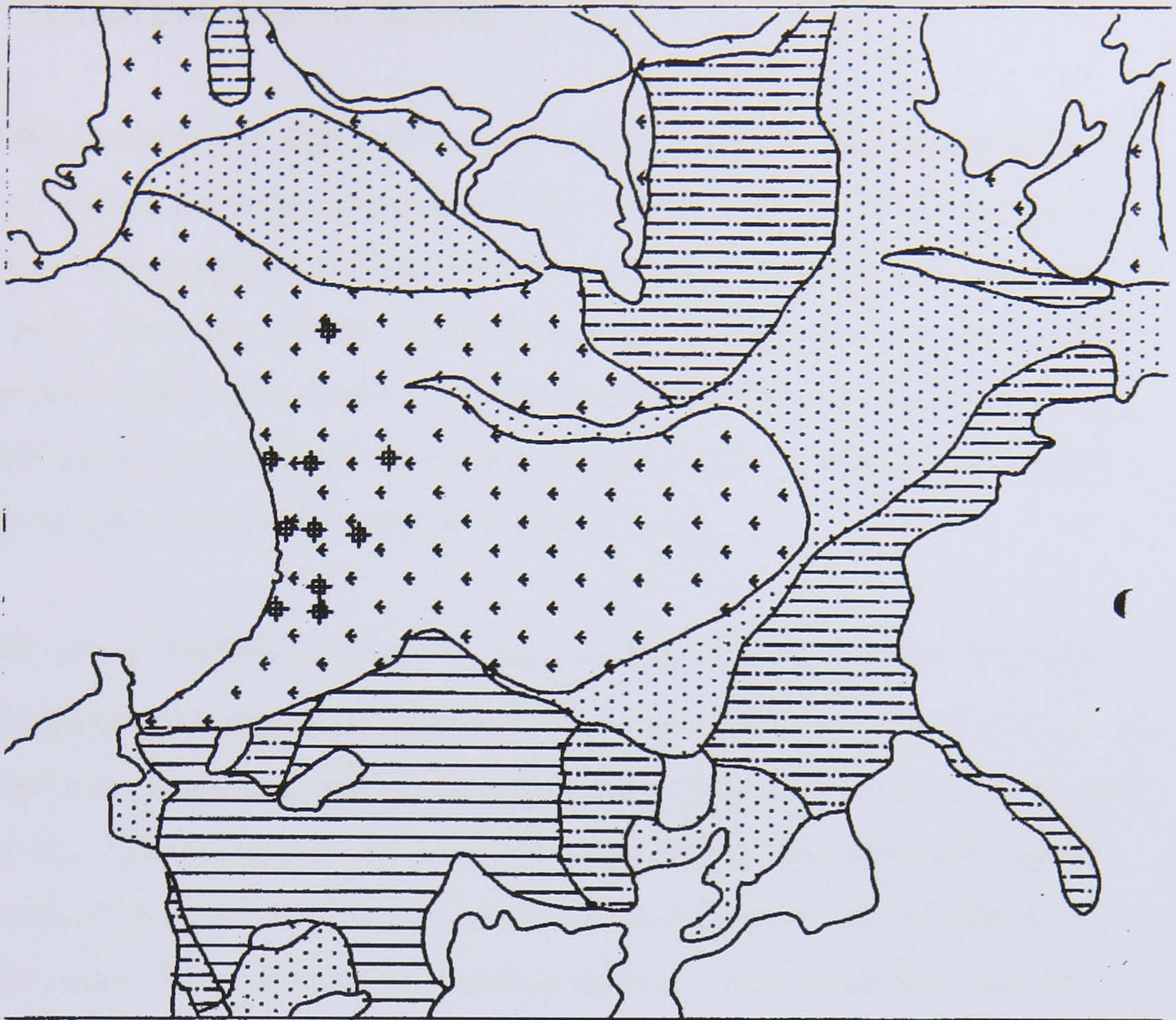


Figure 3.3 Soil types for the Argolid Valley (from Poulouvassilis et al, 1994, p. 58).



## Vertical hydraulic conductivity

Part of the reason for the difference in classification between geology and pedology is that in volumetric terms the soil represents an insignificant proportion of the phreatic aquifer (i.e. containing water which is still part of the hydrological cycle, rather than fossil water). However, it is very important hydrogeologically because of its location at the interface between the geosphere and atmosphere (and biosphere and hydrosphere). Generally a large proportion of the water in phreatic aquifers has passed over and/or through the soil at some point in the hydrological cycle.

The bulk vertical hydraulic conductivity,  $K_{h_z}$ , of a large volume of aquifer may differ from the horizontal hydraulic conductivity of the same volume for several reasons. The geological beds, which compose the internal structure of the aquifer, lie approximately horizontally. Thus horizontal flow is parallel to the internal structures of the aquifer, while vertical flow is perpendicular. Therefore the existence of any beds with a low hydraulic conductivity (aquiclude) will reduce the bulk vertical hydraulic conductivity disproportionately greater than the horizontal hydraulic conductivity.

Another reason is due to the variation of hydraulic conductivity with saturation of the aquifer. If the aquifer is not saturated (the pore spaces are not filled with water) the reduction in hydraulic conductivity is exponential with decrease in saturation. This situation is called unsaturated flow (cf. Section 4.1.4).

Whereas in the main aquifer unsaturated flow can be effectively ignored since saturated flow will always dominate, except in the limiting case where the aquifer is drained of water. However, in the soil and sub-soil, the intermittent nature of precipitation events means that unsaturated flow will tend to be the predominant flow regime. The main effect of unsaturated flow through the soil is to delay precipitated water from reaching the aquifer.

As can be seen from Figure 3.3, a layer of clay, which has low hydraulic conductivity,



covers the central plain of the Argolid. This means the negligible amounts of precipitated water percolate into the aquifer from the central plain. Most precipitation will either run off the land surface into streams and rivers, or be used directly by agriculture. The main recharge of the aquifer is via the periphery of the plain and by inflow from the karstic mountains surrounding the valley.

### 3.2. CLIMATE

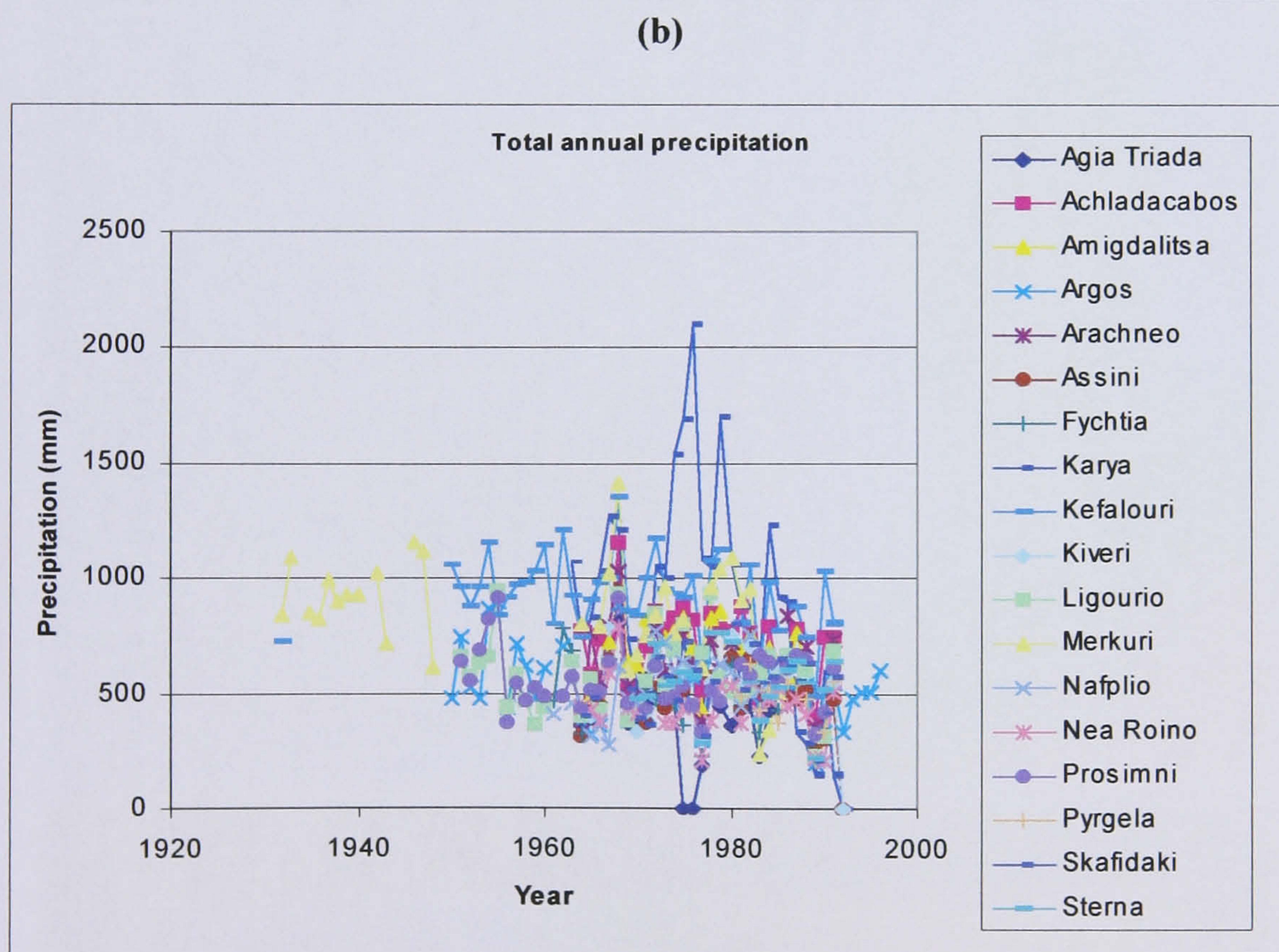
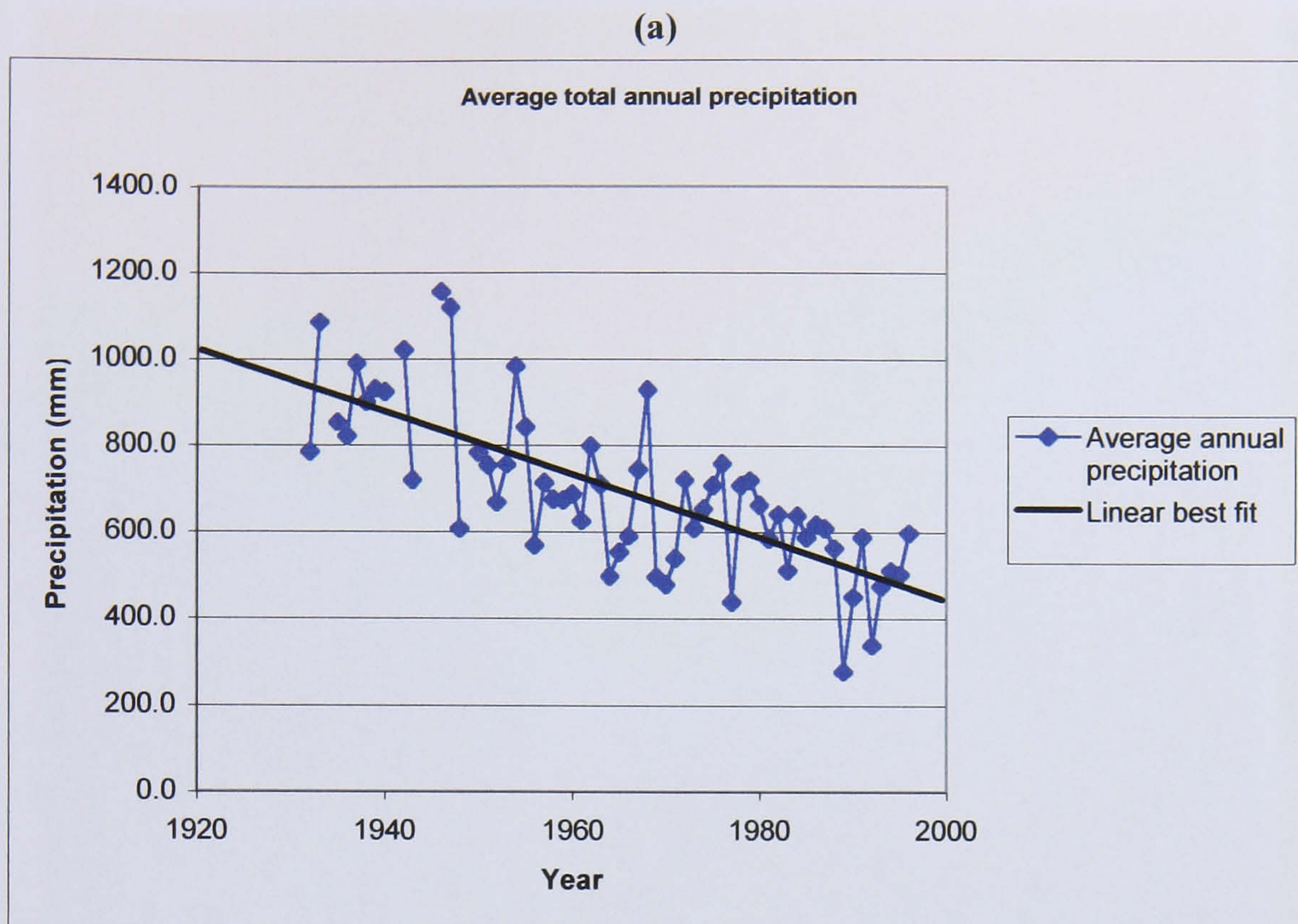
Fresh water is only a transient state that is a result of the hydrologic cycle. This is the cycle of evaporation - precipitation - advection, which transports water from the oceans (hydrosphere), to the atmosphere to be deposited directly back into the oceans or onto land by precipitation. The fraction of water that is precipitated onto land then flows under the influence of gravity downhill to eventually return to the sea. It is the fraction of water on dry land that is of primary concern to man and historically many great civilisations have been centred around the control of water (Newson, 1997, page 3).

Water upon the surface of the earth comes from two possible sources (ignoring artificial processes such as desalination). Either it has reached the surface by precipitation from the atmosphere or it has come from beneath the ground, by either man-made or artificial extraction.

#### 3.2.1. *Precipitation*

Precipitation varies greatly both spatially and temporally, with subsequent impacts upon the quantities and flows of water upon the surface. Figure 3.4 (a) and (b) show the annual variation in total annual precipitation at all meteorological stations (AUA report) while figure 3.5 shows the spatial variation in average annual precipitation compiled from the meteorological stations used in figure 3.3. Figure 3.6 shows the locations of the meteorological stations used to form this dataset.





**Figure 3.4 Total annual precipitation at meteorological stations within the Argolid Valley: (a) average total annual precipitation (for all stations with data in a given year); (b) records at individual stations.**



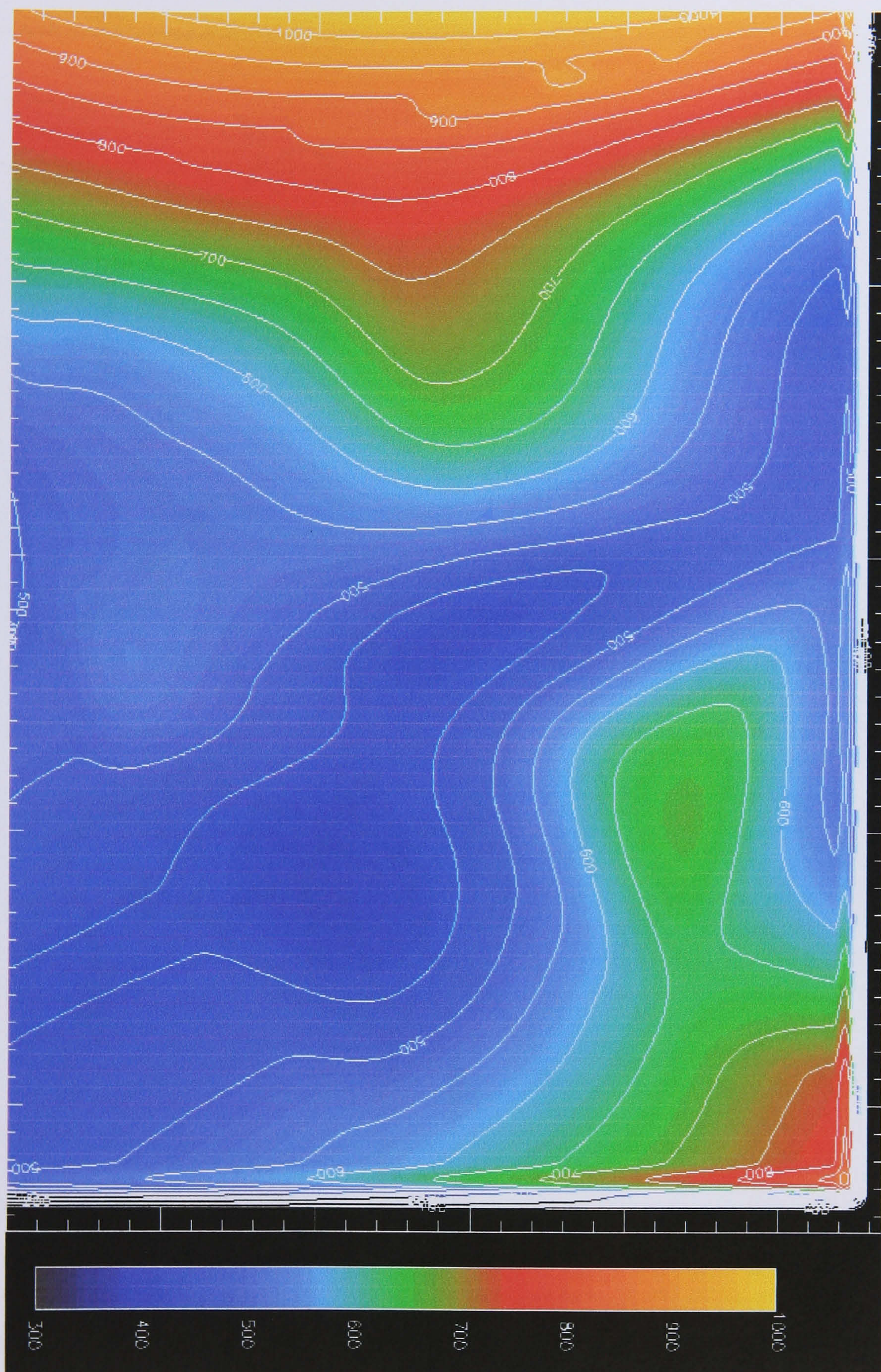
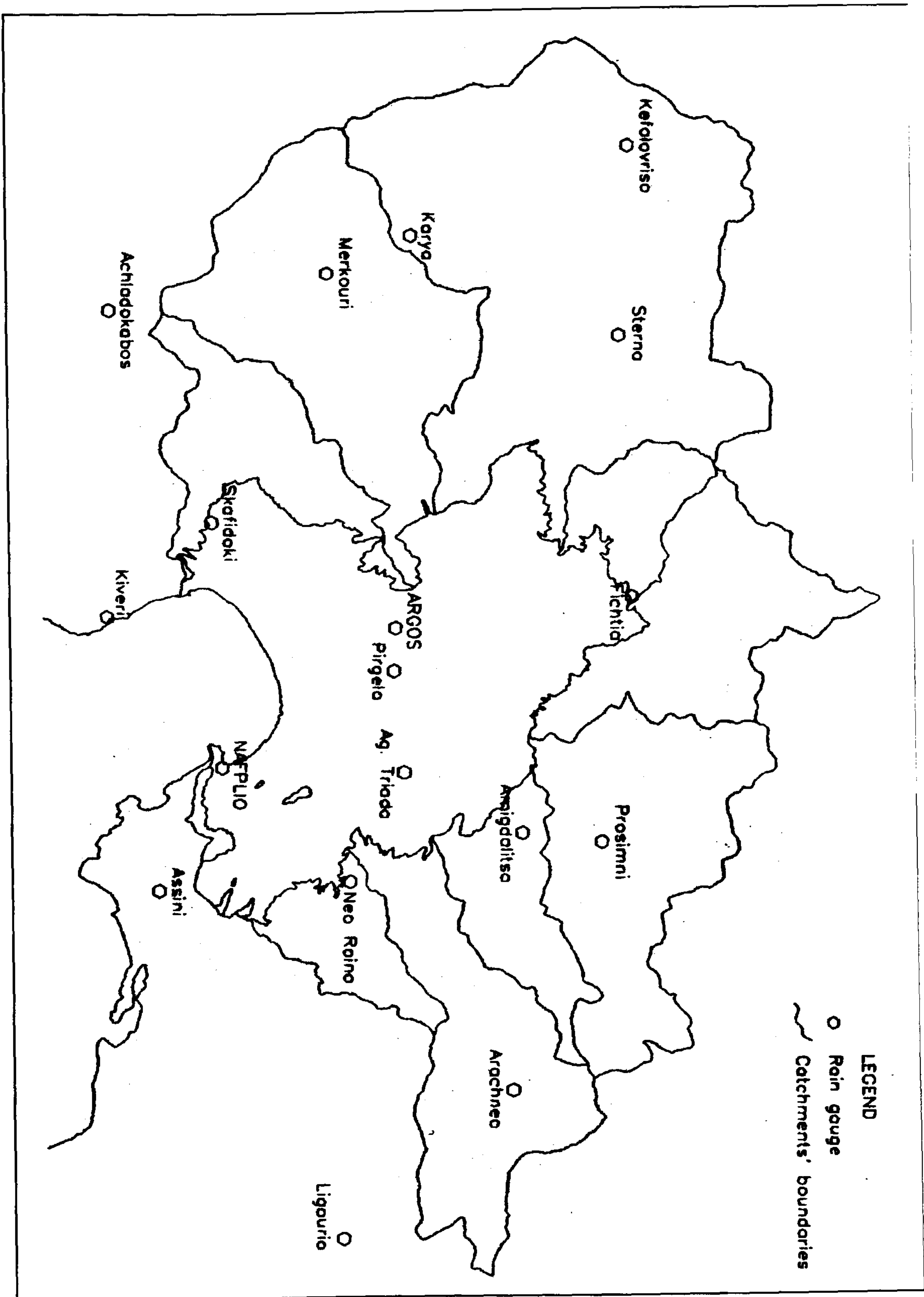


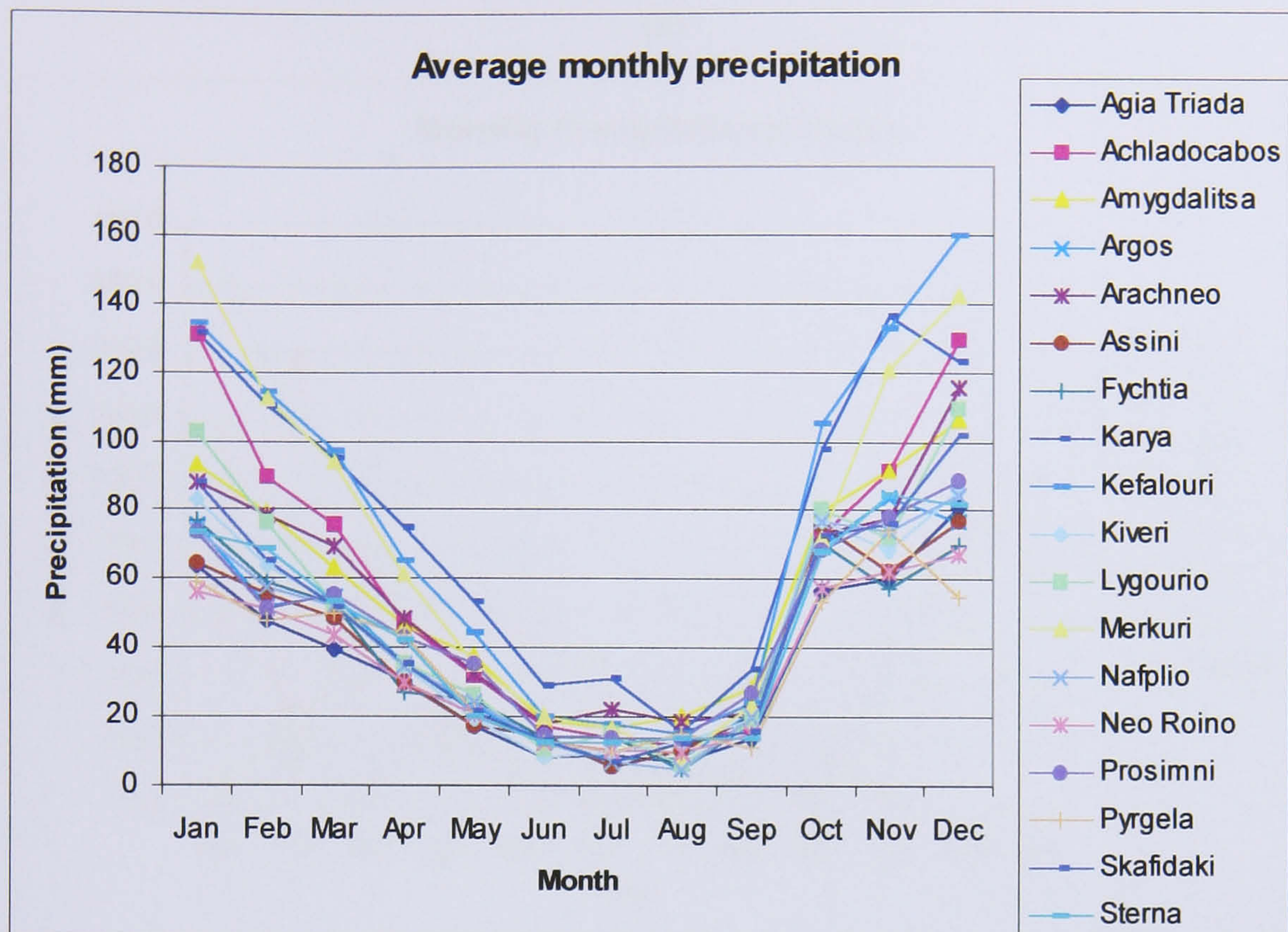
Figure 3.5 Spatial distribution of average annual precipitation. Model grid is the same as in Figure 3.1.





**Figure 3.6 Location of meteorological stations in the Argolid (from Poulouvassilis et al., 1994, p. 13).**





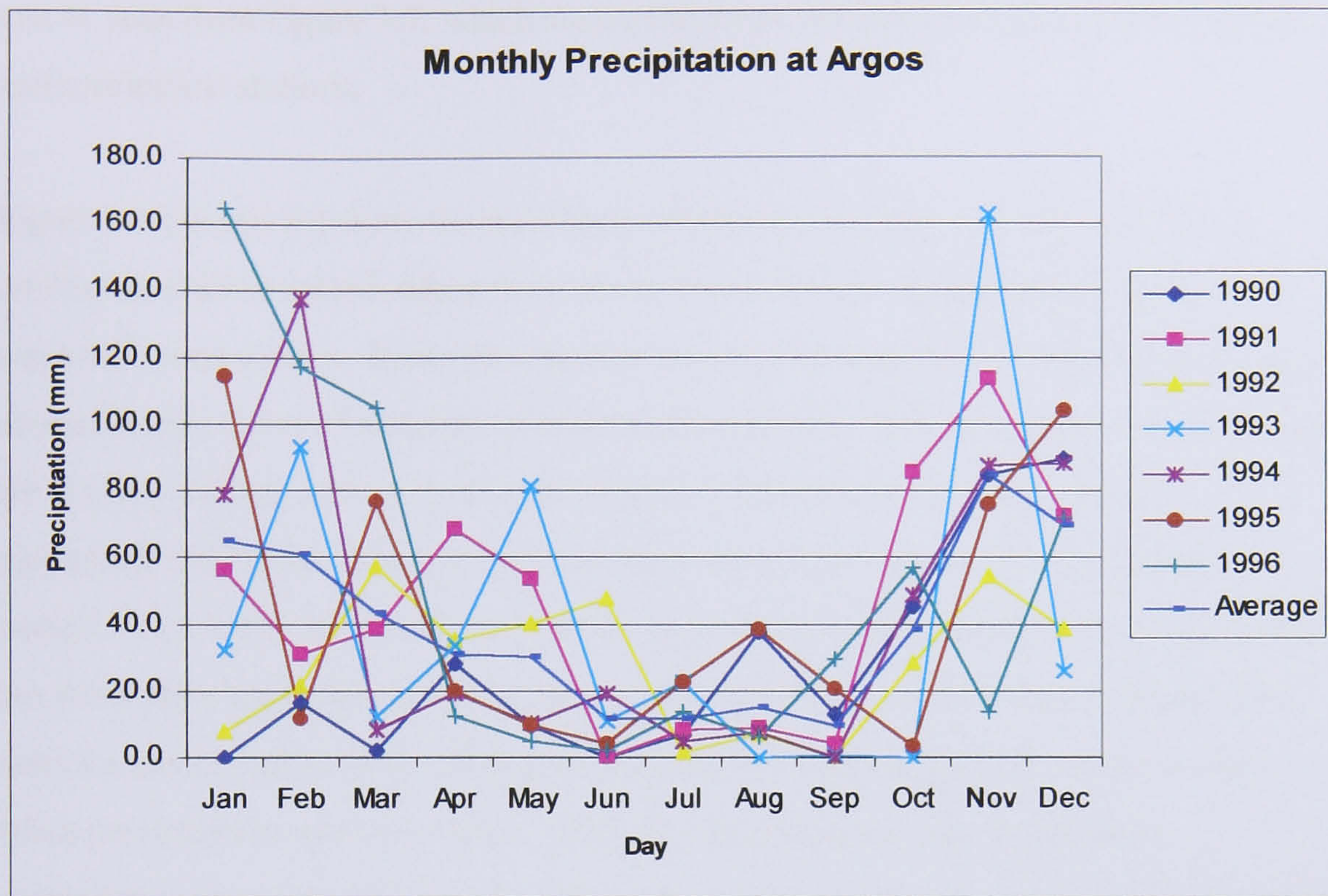
**Figure 3.7 Average monthly precipitation for all meteorological stations (Poulovassilis et al. 1994). N.B. Data for individual stations is not necessarily contiguous or contemporaneous.**

. It can be seen from Figure 3.4 (a) that there is a distinct decreasing trend in the average total annual precipitation. This trend is seen to a lesser extent in the data for individual meteorological stations (Figure 3.4 (b)) where only the meteorological station at Nafplio shows a significant increase in precipitation. Overall, the best description of the general trend meteorological stations is that there has been a proportionate decrease in the levels of precipitation.

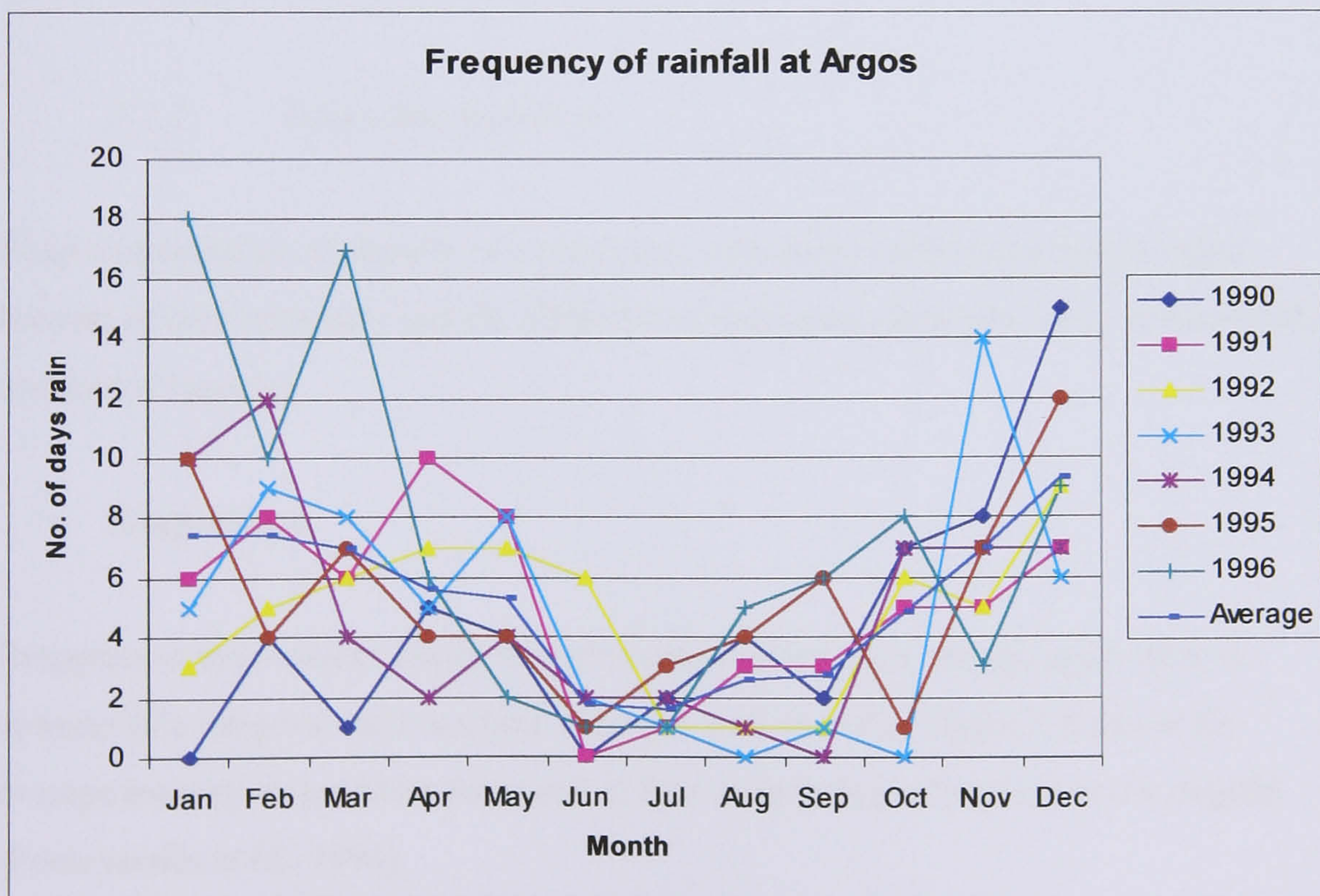
Figure 3.7 shows the average variation in monthly average precipitation for all stations in the Argolid (Poulovassilis et al. 1994)). It can be seen that there is a significant variation in the monthly rainfall throughout the year, and in the total rainfall each year. There is a



(a)



(b)



**Figure 3.8 Monthly rainfall data for Argos (1990 to 1996): (a) precipitation (mm); (b) rainfall frequency (days per month).**



“rainy season” from October to March, and a “dry season” from June to September, as can be seen from Figure 3.7, which shows the mean monthly average rainfall for all the meteorological stations.

Figure 3.8 (a) and (b) show the monthly precipitation and the number of days each month on which it rained, taken from seven years of daily rainfall data at Argos meteorological station. It can be seen that the monthly and annual variation in rainfall is caused by two types of variation in diurnal precipitation. The first type of variation is in the number of days when precipitation occurs. When monthly and/or annual precipitation is higher than normal, there tend to be more days when precipitation occurs. Vice versa, when monthly and/or annual precipitation is lower than normal there are fewer days when precipitation occurs. The second variation is that when monthly and/or annual precipitation is lower, the amount of precipitation that occurs on days when precipitation occurs is lower. The combination of the two is that when precipitation for a year is lower than the average, it rains less frequently and less rain falls on those days than in a "wet" year.

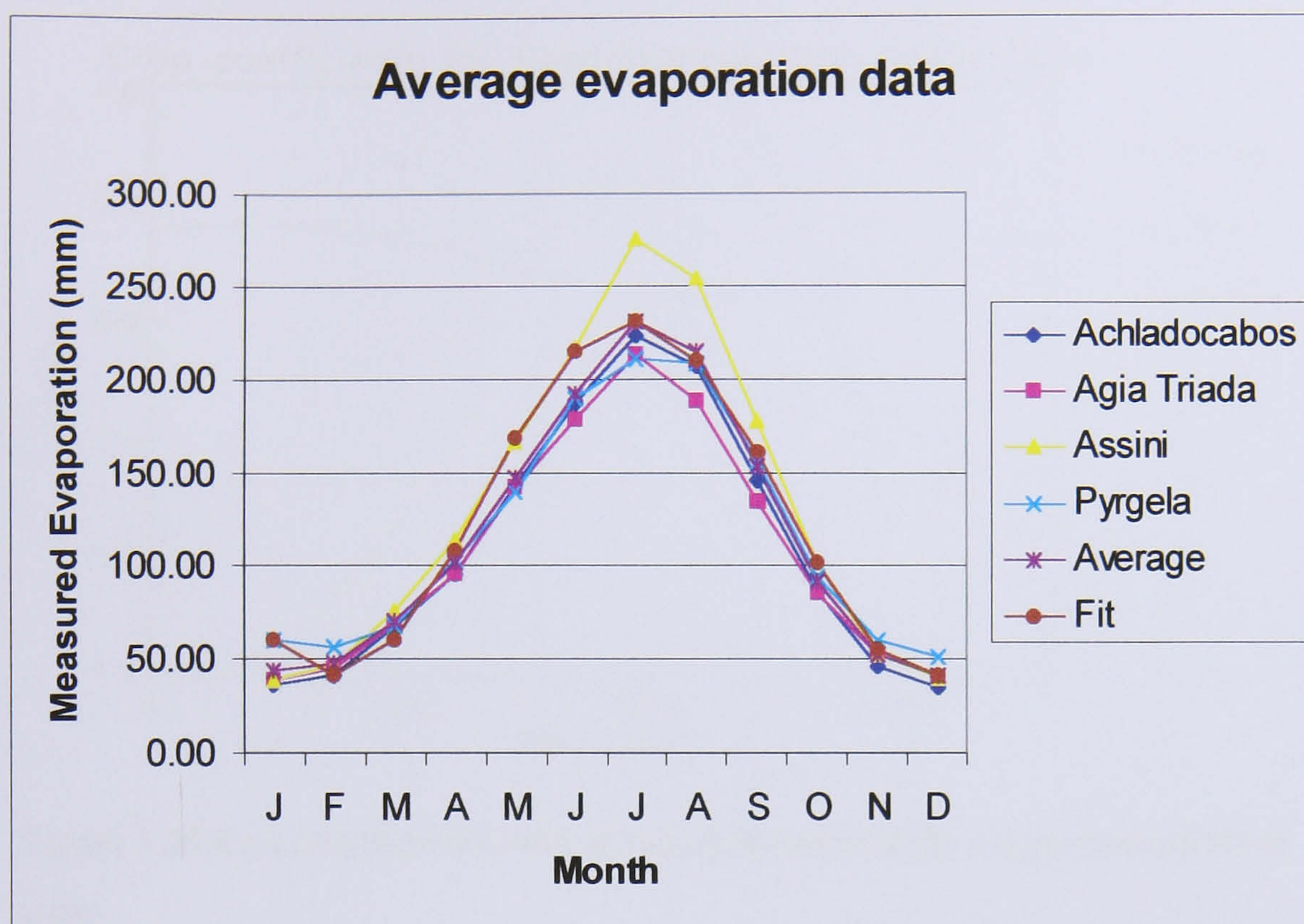
### 3.2.2. *Evapo-transpiration*

Evapo-transpiration is actually two processes, evaporation and transpiration, which because of their proximity and the difficulty of measuring them separately, are normally considered together.

#### **Evaporation**

Evaporation shows lower spatial variation than precipitation, though again there is considerable temporal variation both diurnally and annually. Figure 3.9 shows the average monthly evaporation measured at four meteorological stations in the Argolid (Poulovassilis et al., 1994).





**Figure 3.9 Monthly average evaporation (mm) in the Argolid Valley.**

The evaporation measured at these stations is from open pans of water. It is hard to categorise the small spatial variation from only four locations, however it does appear that evaporation rates increase marginally with altitude. The temporal variation is explained by the variation in air temperature and the amount of sunlight through the year.

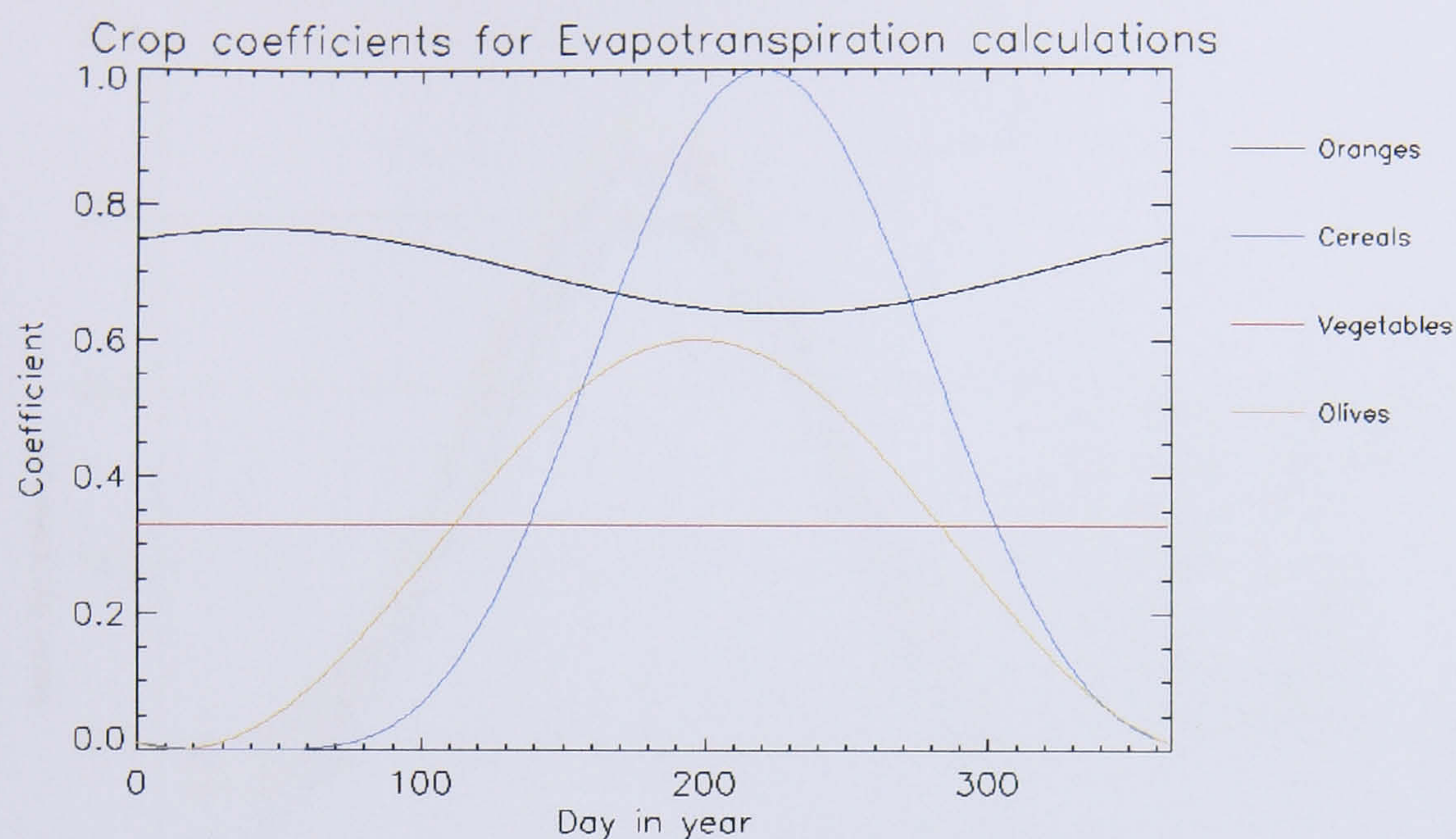
### Transpiration

As stated in Chapter 4, transpiration is normally included in calculations of evapo-transpiration as a crop coefficient that modifies the evaporation rate to an empirical evapo-transpiration rate. Typical values of the crop coefficients are shown in Figure 3.10 (after Schwab et al., 1993; Wild, 1988).

#### 3.2.3. Temperature.

Low temperature and the associated occurrence of frost is one of the main limiting



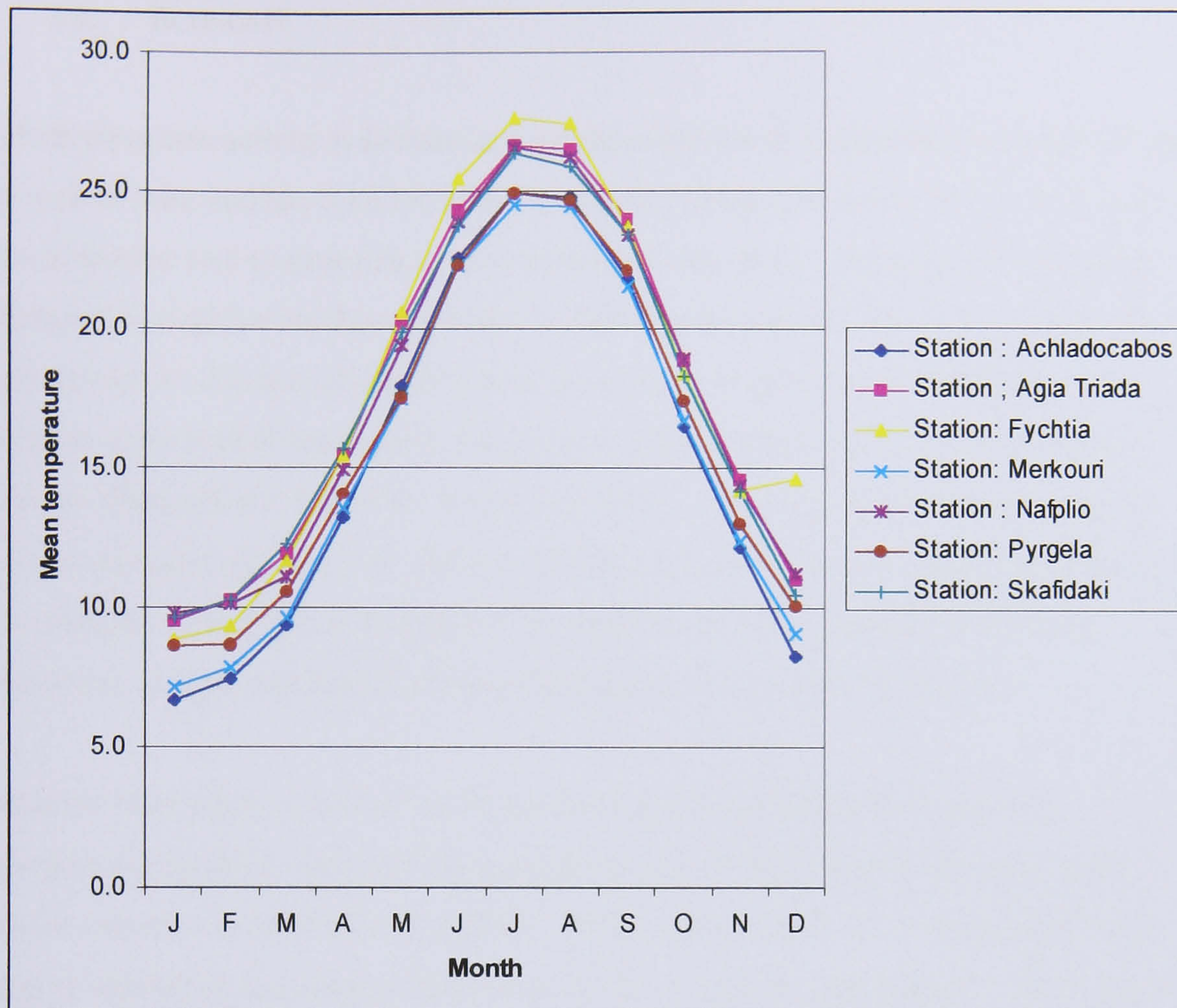


**Figure 3.10 Crop coefficients used to calculate model daily evapo-transpiration rates.**

factors determining the geographical distribution of plant species (Forbes and Watson, 1992, p.102). In particular, citrus crops are particularly sensitive to low temperatures, both through the possibility of chilling injury to fruit, and the susceptibility to frost damage of the flowering stage of growth (Forbes and Watson, 1992, p.102). In general, the ideal temperature for the growth of citrus fruit is in the region of 20°C to 30°C (FAO, 1995; Fitter and Hay, 1987, p.210), while the ‘killing temperature’ is –2°C (FAO, 1995).

The occurrence of frost varies with location in the Argolid Valley with, on average, 5 days of partial frost occurring at the coast, and 25 days, occurring in the interior (Poulovassilis et al., 1994). The mean monthly temperature varies between 8°C and 28°C (see Figure 3.11) however minimum and maximum air temperatures of –5°C and +45°C, respectively, have been recorded (Poulovassilis et al, 1994).





**Figure 3.11 Mean monthly temperatures in the Argolid Valley.**

Because of the major effect low temperatures have upon citrus crops, the farmers in the Argolid Valley use technological means to avoid frosts. These consist of air mixers, specifically designed to raise the air temperature at ground level over a wide area, and the operation of sprinkler irrigation systems. The use of sprinkler systems is of particular importance for groundwater, because water from the spring at Anavolos is often too dense to be used for sprinkler irrigation (Allen et al., 1995). Thus, in years, when frost occurs more frequently than the average, groundwater use can rise considerably. Furthermore, farmer interviews have revealed that farmers who use automatic systems for the control of sprinkler irrigation for frost prevention, tend to set the system to activate at temperatures above 0°C (i.e. at 1°C or 2°C). This has the effect of greatly increasing the number of days when sprinkler irrigation will be used.



### 3.3. ECONOMY

Much economic activity is focused around the control and manipulation of water for the benefit of man, and has been for many thousands of years (Newson, 1997). This varies from massive civil engineering structures to hand-dug wells. The larger structures are designed to regulate the flows of water so that in particular the effects of "catastrophic" events such as floods or droughts can be avoided, or at least greatly mitigated. Such structures have traditionally been directly controlled and paid for by government (e.g. Hoover Dam and the Tennessee Valley Authority). This is partly because the benefits are not directly monetary, but rather in the form of more general economic benefits due to reduced environmental uncertainty. In addition, the cost of building such large structures as dams and canals is beyond the means of a private organisation.

Because these large structures are constructed and controlled by government or government agencies, they are highly regulated and monitored, and the impact upon water resources is often known in detail. At the opposite end of the scale, small wells dug by individual or groups of farmers are often completely unregulated. There may be no control over location of wells/boreholes and no measurement of the effect upon the surrounding water resources. Thus, that the extraction of water is affected solely by the farmers' perception of environmental conditions (soil moisture, crop requirements etc.).

The difference in regulation is a result of the difference in geographical scale. However, in both cases water is treated as a common resource. At the larger scales, only government can ensure that use and development of water resources occurs in an equitable fashion. At the smaller scale, individuals have (defined by the legal code for the locale) rights of access to this common resource.

This is the situation in the Argolid. The main sources of water for irrigation are the canals and by extraction of groundwater through boreholes. A department of the national government, in conjunction with local representatives, regulates access to the canal water (Blatsou, pers. com.). Farmers are allocated an amount of time during which



they have access to the canal water. In contrast, the only restriction on boreholes is that no new borehole may be constructed within fifty (50) metres of another, though it is not clear (to me) whether that includes unsuccessful or failed boreholes. Further there is no monitoring of the amount of abstraction through the boreholes, and the only cost is the price of the energy used to raise the water from beneath the ground to the surface.

The result of water being effectively free is that there is no incentive for users to restrict their use, or if they have sufficient or surplus water for their own needs, to use water efficiently. In the Argolid this has resulted in the main form of irrigation delivery remaining flood irrigation, a method that has remained more or less unchanged since the turn of the century. This is partially because technology has increased the farmers' ability to abstract water from boreholes, both in terms of volumetric flows, and in terms of the depth from which water can be recovered. Whereas before WWII water pumps were wind or animal powered, after World War II internal combustion engines were used, to the present day when Electro-mechanical pumps are placed within the boreholes below the level of the water table (Allen et al., 1995).

The lack of change in the form of irrigation is not due to any lack in technological progression. In many arid countries highly efficient forms of irrigation have been devised, which both minimise the loss of water due to evaporation, and maximise the amount of water available to the crop. However, in arid countries the drive for technological change has been that the demand for water exceeds the supply, thus encouraging all users to be efficient in the use of what water supplies they have access to. Because water has only recently been perceived as a major problem in the Argolid, there has been no conversion to more efficient forms of irrigation. Furthermore, for sociological reasons many farmers are limited in their ability to change their agricultural practices for example when they have a second income, which limits the amount of time which they can devote to agriculture (Allen et al., 1995).



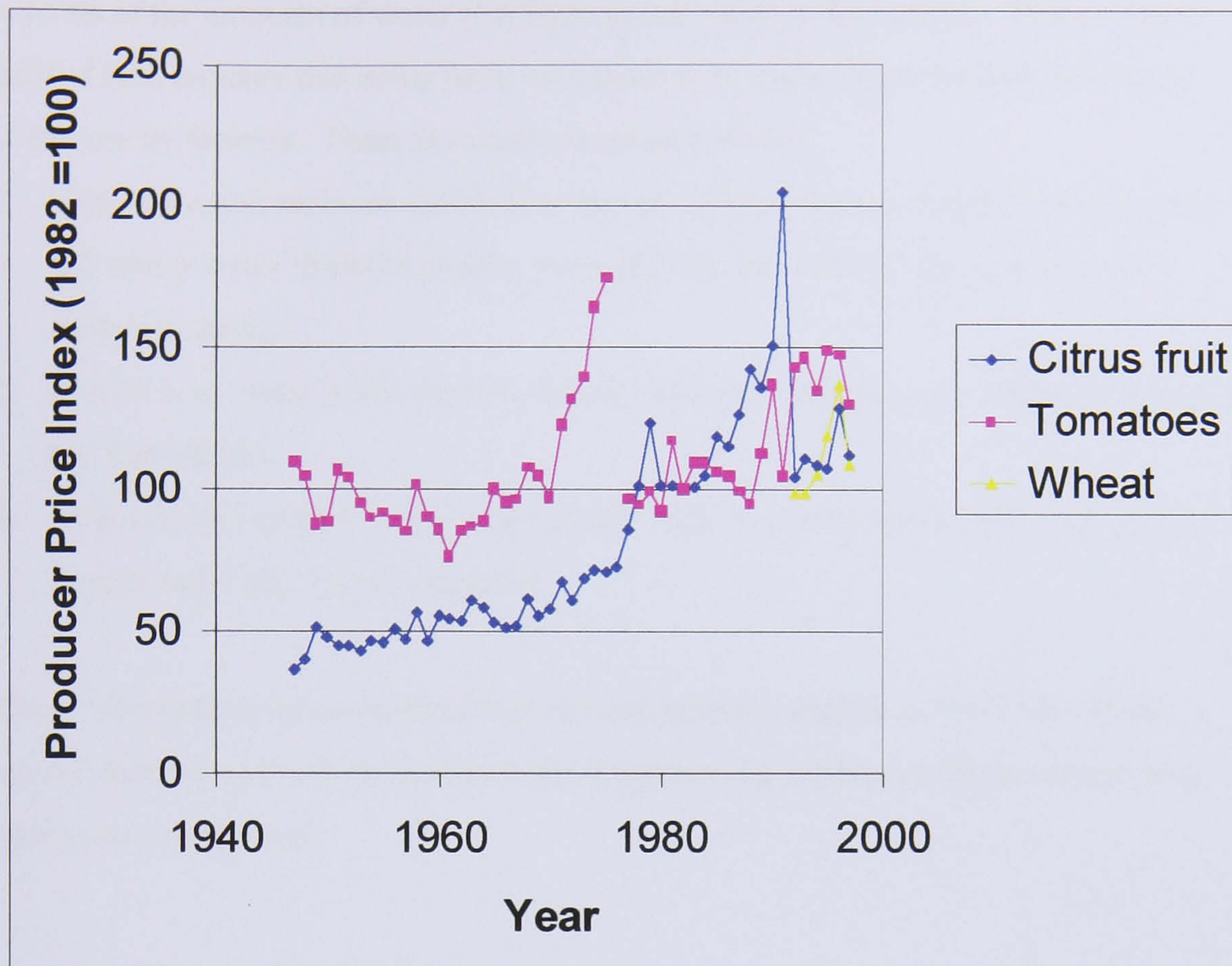
### 3.3.1. Crop selection

One of the main limitations of the econometric model as Allen et al. (1995) used it was the lack of a history of crop prices available with which to drive the model historically. This resulted in the model being artificially constrained to behave in a manner that resembled the actual historical process (Allen, *pers. comm.*). Though there is no data available for actual crop prices in the Argolid Valley, there does exist a history of producer price indices from the Bureau of Labor Statistics in the U.S.A. (1998). Figure 3.12 shows this crop price data. There were four crop types used in the 7-zone model (citrus fruits, cereals, vegetables and olives). There is no index for olives in the U.S data since the US is not a major grower of olives. Actual producer prices for crops are also available, albeit for a shorter time period (FAOSTAT, 1999), which agree closely with the Bureau of Labor Statistics data. These prices do not take account of the effects of inflation upon Greek prices, so the Bureau of Labor Statistics data will be used to represent the relative changes in price between crops, with the actual prices at a fixed point in time taken from FAOSTAT (1999).

In the model of Allen et al. (1995) only citrus fruits and vegetable crops require irrigation. It is assumed that cereals and olives do not require irrigation, as the data from the Argolid shows that only a very small proportion of land used for cereals and olives is actually irrigated.

It can be seen from Figure 3.12 that there is a significant difference in the price histories of citrus fruits and vegetables (making the assumption that tomatoes are a reasonable analogue for all vegetables). The price of vegetables has on average had a very gentle rate of price increases, but has had a high level of price variability, presumably associated with variations in production. Citrus fruits experienced dramatic price increases in the late 1970's making them a far more attractive crop to farmers. Furthermore, following the association agreement between Greece and the European Community in 1962 led to reductions in tariffs on Greek exports to Europe, with tariffs being completely removed in 1975 (Ritson and Harvey, 1997, p.45). Greece's accession to the EC in 1981, opened





**Figure 3.12 Producer price indices for three crops in the U.S.A. (U.S. Bureau of Labor Statistics, 1998). 100 = prices in 1980.**

Greek agriculture to the Common Agricultural Policy, with support pricing and export subsidies. The combination of these effects has been to vastly expand the market for Greek agricultural produce, particularly in areas such as citrus fruit where there was relatively little production in the rest of the EC, and to remove the natural variations in price resulting from overproduction. This has resulted in large proportions of some crops being withdrawn from the market as production exceeds demand (Ritson and Harvey, 1997, p.253)

### 3.3.2. *Water use*

Farmers use of groundwater is almost completely unregulated. Therefore there are no



records of the amounts of water that farmers extract from the aquifer. This complete lack of data requires that some basic assumptions be made about the daily pattern of water use by farmers. These assumptions are as follows:

1. if there is a soil moisture deficit (i.e. the soil is drier than is required) then the farmers will pump water from the aquifer, provided that the water in the aquifer is of sufficient quality;
2. if there is no water in the aquifer, farmers will use water from the canal for irrigation, if it is available;
3. if there is no available water in the aquifer, and no connection to the canal then the farmers will “ask” to be connected.

These assumptions are consistent with the assumptions implicit in the econometric model, that farmers will try and meet the irrigation requirements of their current crop choice on a daily basis.

### 3.4. SUMMARY

Though there is significant annual rainfall in the Argolid, the temporal distribution results in there being essentially no rainfall in summer when crops require it most, forcing the farmers to rely on groundwater or canal water for irrigation. The extraction of water from boreholes is unregulated, so that once a borehole has been created there is no legal restriction on the amount of water that can be extracted. Finally, the geological characteristics are such that the aquifer in the central plain has a high horizontal conductivity, but a low vertical hydraulic conductivity, this being the result of the interleaving of clay layers with sandy layers. Thus, little rainfall will percolate into the aquifer in the central plain, but seawater can easily flow into it if the water level within the aquifer drops below sea level. The result is a water resource system that is both prone to over-exploitation and to rapid salination once over-exploitation has taken place.



## CHAPTER 4: THE WATER RESOURCE SYSTEM MODEL

This chapter will discuss the different components and processes that comprise the water resource system (as I defined it in Chapter 1) and examine the linkages between them. I will then describe the structure of the numerical model.

### 4.1. HYDROLOGY/HYDROGEOLOGY

Hydrological and hydrogeological systems have very different characteristics despite being very closely related disciplines. While flow across the surface is essentially two-dimensional, flow beneath the ground can be distinctly three-dimensional. Surface flow interacts with atmosphere, pedosphere and biosphere in numerous complex ways, whereas subsurface flow is directly isolated from these effects. The central parts of the water resource system in the Argolid are the aquifers containing groundwater, the flow of water and the associated transport of solutes. Taking each part in turn:

#### 4.1.1. *Sub-surface flow*

The flow of water through aquifers was first theoretically described by Darcy in 1856 (Domenico and Schwartz, 1990, p. 33). Darcy's Law states that the volume of water moving in a certain time through a certain size opening is proportional to the vertical drop of the water from height to another divided by the distance the water has travelled:

$$Q = -KA \frac{dh}{dl}$$

where:

$Q$  = volumetric flow of water per unit time [ $\text{m}^3\text{s}^{-1}$ ];

$A$  = cross-sectional area through which the water flows [ $\text{m}^2$ ];

$h$  = difference in height [m];

$l$  = distance travelled [m];

$K$  = hydraulic conductivity [ $\text{m}^2\text{s}^{-1}$ ].



Thus we can see that in order to be able to model the flow of water through the aquifers, it is necessary to have information about the geology of the area, in particular regarding the distribution of different rock types and their hydraulic conductivities.

The constituent equation for water flow through a porous medium is derived by combining Darcy's Law with a three-dimensional water balance (conservation of mass) equation. The water balance equation states that:

$$\text{outflow} - \text{inflow} = \text{change in storage}$$

or mathematically:

$$\left( \frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} + \frac{\partial q_z}{\partial z} \right) = -S_s \frac{\partial h}{\partial t} + R$$

where:

$q_x, q_y, q_z$  = volumetric flows parallel to the  $x, y$ , and  $z$  axes respectively;

$x, y, z$  = the co-ordinate axes;

$t$  = time;

$h$  = head, height of the water surface within the aquifer;

$S_s$  = specific storage, the volume of water released from storage per unit change in head ( $h$ ) per unit volume of aquifer;

$R$  = recharge, volume of inflow to the system per unit volume of aquifer per unit time.

The normal technique in hydrogeology is to combine Darcy's Law (in three dimensions) with the water balance equation to give the non-linear Boussinesq equation:

$$\frac{\partial}{\partial x} \left( K_x \frac{\partial h^2}{\partial x} \right) + \frac{\partial}{\partial y} \left( K_y \frac{\partial h^2}{\partial y} \right) + \frac{\partial}{\partial z} \left( K_z \frac{\partial h^2}{\partial z} \right) = 2S_s \frac{\partial h}{\partial t} + 2R$$



It can be seen from the Boussinesq equation that knowledge of the hydraulic conductivity and storage capacity of the aquifer is crucial if the flow of water and change in head within the aquifer are to be predicted.

If the Boussinesq equation is used to calculate the change in water heads with time, then the water flows that generated that change are normally found (McDonald and Harbaugh, 1988) by differentiating across the water head surface. This method is prone to generate errors in the calculated flows, which will then propagate through the solute transport that is associated with the flow of water. Since the solute concentration (salinity) is a critical factor in the interaction with the economic system, because salinity determines the farmers' ability to use water for crop irrigation, it is desirable and appropriate to model the water flows directly, rather than use the Boussinesq approach. Furthermore, the historical hydrology data being used to calibrate the model is of a more qualitative form than is normally used for "traditional" hydrological models. This means that the hydrogeological model may not be calibrated to the same accuracy as standard models, and further militates against the use of standard models because of their high data requirements. Instead, Darcy's Law is used to calculate the water flows in certain directions, and then calculate the effect of these flows upon the head using the continuity equation. This is less efficient computationally than applying the Boussinesq equation and its derivatives directly, but avoids the propagation of errors, and is an approach used in oceanographic modelling where the calculation of water flows is important (Proctor and Flather, 1983).

The computation proceeds as follows. At each new timestep the new head of water is calculated based upon the head in the previous time step plus the flows into (and out of) the cell. Because the basement beneath the aquifer is assumed to be impermeable, there are no flows across the lowest boundary of the aquifer. Vertical flows between the aquifer and the land surface come from the "farmers" decision to pump water from (or conceivably into) the aquifer and from percolation down into the aquifer from the soil/surface layer. It is possible (if desired and if data are available for calibration) to include more than one layer within the aquifer. Layers such as sub-soil which would have an intermediate position between the aquifer and the soil/surface.



#### 4.1.2. *Solute transport*

When water flows, it carries with it dissolved and suspended material. Because subsurface flow occurs within a porous body, the transport of suspended matter with a size greater than or similar to the pore size within the aquifer may be ignored. For dissolved material there may be changes in the concentration of the solute by the advection of the solution, the dispersion of the solute and possible chemical reactions between the solution and the matrix of the aquifer. Numerically, solute concentrations are placed at the centre of each grid cell. Given that flows are calculated at the boundaries between each cell, this implies that instant mixing occurs within the cell.

#### **Advection**

The transport of solutes by advection is simply the associated transport of the solute with the solvent (water). It is the easiest to handle numerically, as it simply requires the paths of hypothetical particles embedded in the flow to be calculated.

In the model this is handled by creating a set of arrays indicating the direction of flow around each location within the model domain. This ensures that salt flows occur in the same direction as the water flow. This is necessary numerically because properties such as volume and concentration are located at the centre of each cell whereas flows are calculated at the edge of each cell.

#### **Dispersion**

Dispersion of a solute normally occurs due to the heterogeneity of the medium through which flow is occurring. It is often represented as being the result of a statistical distribution of flow paths and velocities through a heterogeneous medium, with the scale dependant upon the size of the heterogeneity. In fact it is caused by turbulence



within the flow and the presence of solute concentration gradients within the solution as the flow paths through the heterogeneous medium diverge and converge. Dispersion is most important when considering solute transport away from a point source.

## **Reaction**

The solute can react chemically with other solutes in the groundwater, or with the matrix of the aquifer. In both cases, the variation in the reduction of solute over time will depend upon the specific chemical reaction that is occurring. Thus, the changes in solute concentration will vary according to the composition of the aquifer matrix, which may be changing due to the reactions taking place. Further complications may be caused in aquifer matrices that are rich in clay minerals. The pore size and heterogeneity of the aquifer matrix may be changed by the chemical reactions between clay minerals and the solute allowing grains to fuse together.

### **4.1.3.      *Surface flow***

Surface flow takes two basic forms: flow across the land surface; and flow within streams and rivers. Obviously the two forms are closely linked since the majority of water within streams and rivers will have flowed across the land surface before reaching the river, and equally when the volume of water flowing within a river exceeds the capacity of that river and the water flow expands beyond the confines of the normal river (flooding).

#### **Flow of water across the land surface.**

Apart from the special case of flooding, water will only flow across the land surface as a result of precipitation. Thus this type of flow is of a very transient nature, with the duration and magnitude of the flow closely dependent upon the intensity and duration of the precipitation, and the topography of the land surface.



Because of the transient nature of this type of flow and the wide variety of conditions that can exist at the land surface itself (vegetation, permeability of the soil, distance to the nearest stream) hydrologists have derived purely empirical equations to methods to predict this flow. A common example is the Time-Area Method (Shaw, 1996):

$$Q_T = \sum_{k=1}^T i_{(T-k)} \Delta A_k$$

where:

$Q_T$  = volumetric flow at time T;

$i$  = rainfall intensity;

$\Delta A_k$  = area.

This states the volumetric flow out of the catchment is a function of the rainfall intensity and the area of the catchment.

### **Flow of water in streams and rivers**

While the equations describing the flow of water bodies of water in channels are well known, in practice it has not proved possible to accurately model the flow of water within rivers. This is because the river modifies the form of its channel by the continuous processes of erosion and deposition, which in turn modifies the flow within the river. Because of the difficulty in modelling these processes, river flow is normally modelled in a semi-empirical way, with the river channel network assumed to be invariant (Jones, 1997, p.190). For the Argolid valley, the most important feature of the river network is that it is seasonal, with all but the largest river drying up completely during the summer months. This greatly reduces the importance of river flows both to the farmers as a source of irrigation, and to the aquifer as a source of recharge.



#### 4.1.4. *Unsaturated flow.*

Between the surface and the aquifers lies the soil. Flow within the soil forms a special regime, with a crucial difference from flow within the aquifer. Hydraulic conductivity is a measure of the ease with which water can flow through a porous medium. It is a parameterisation of many different variables such as the size, number, shape and connectivity of pore spaces within the porous medium (rock). Under saturated conditions, when water fills all the pore spaces within the medium the hydraulic conductivity does not vary with time, though it may still be anisotropic. However, when the aquifer is unsaturated, water does not fill all the pore spaces. This means that the actual area through which water may flow is reduced. Furthermore, factors such as the surface tension of the water and vapour pressure within each pore begin to have an effect. The relative importance of these factors changes as the volume of water within the medium changes. This results in a hydraulic conductivity that varies greatly with the volume of water within the porous medium (Domenico & Schwartz, 1990, p.54).

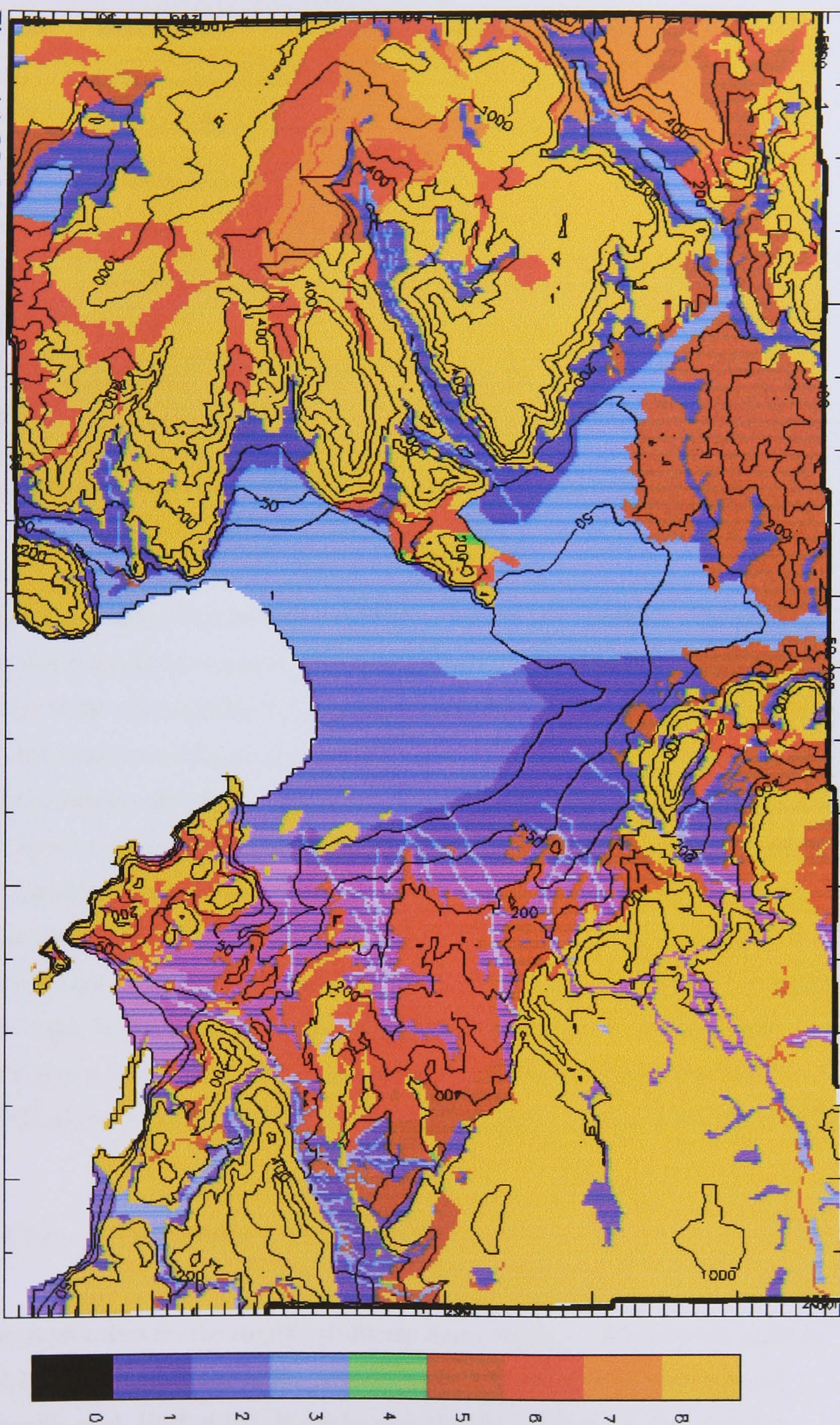
Unsaturated flow obeys the same Boussinesq equation as flow within aquifers. Because of the variable nature and reduced magnitude of the hydraulic conductivity, the magnitude of the flows are both much smaller (and therefore harder to measure accurately) and harder to accurately predict numerically (because the hydraulic conductivity will vary continuously). Standard practice in hydrological models is to treat unsaturated flow as occurring in only the vertical direction (i.e. one dimensionally). This is purely because of the length scales over which flow takes place, the vertical scale of most aquifers being several orders of magnitude smaller than the horizontal scale.

#### 4.1.5. *Geology.*

The aquifer and its properties are obviously of primary importance in controlling the dynamics of the water resource system. While there is a fairly complete description of the geology, there is very little data regarding the *in situ* hydrogeological properties of



Figure 4.1 Model geology data for the Argolid valley. Key refers to Table 4.1.





Key no:	Description	Geological sequence
1	Coarse alluvial sediments	28, 29, 30, 31, 32
2	Fine alluvial sediments	27, 33, 34
3	Alluvial sediments	26
4	Igneous	7,8
5	Sandstones	3, 10, 19, 22, 23, 24, 38, 39, 40
6	Flysch	2, 4, 5, 25
7	Dolomites (& limestones)	1, 11, 12, 13, 21
8	Limestone (karst)	6, 9, 14, 15, 16, 17, 18, 20, 35, 36, 37
<b>Table 4.1 Key to Figure 4.1. Geological sequence numbers refer to Table 3.1</b>		

the different geological formations, or the three-dimensional structure of the geology. The data that is available is restricted to well tests carried out in the central plain, which reveals that in the central plain, the structure is quite complicated with interleaved layers of clays and sands overlying an impermeable base. Because of this, the aquifer will be treated as consisting of a single layer of material, with the soil/surface being treated as a separate layer. Given this simplification, the lack of hydrogeological data, and the existing classification of the geology by age, it is also logical to simplify the description of the geology of the area. The forty different geological classes shown in Figure 3.1 and Table 3.1 are reduced to eight broader types in Figure 4.1, and Table 4.1 indicates how these types relate to the geological classification in Table 3.1. With these 8 geological types, it is possible to use the literature to define a range of possible hydrogeological parameters, which may be suitable to apply to these types in the model.

#### 4.1.6. *Topography*

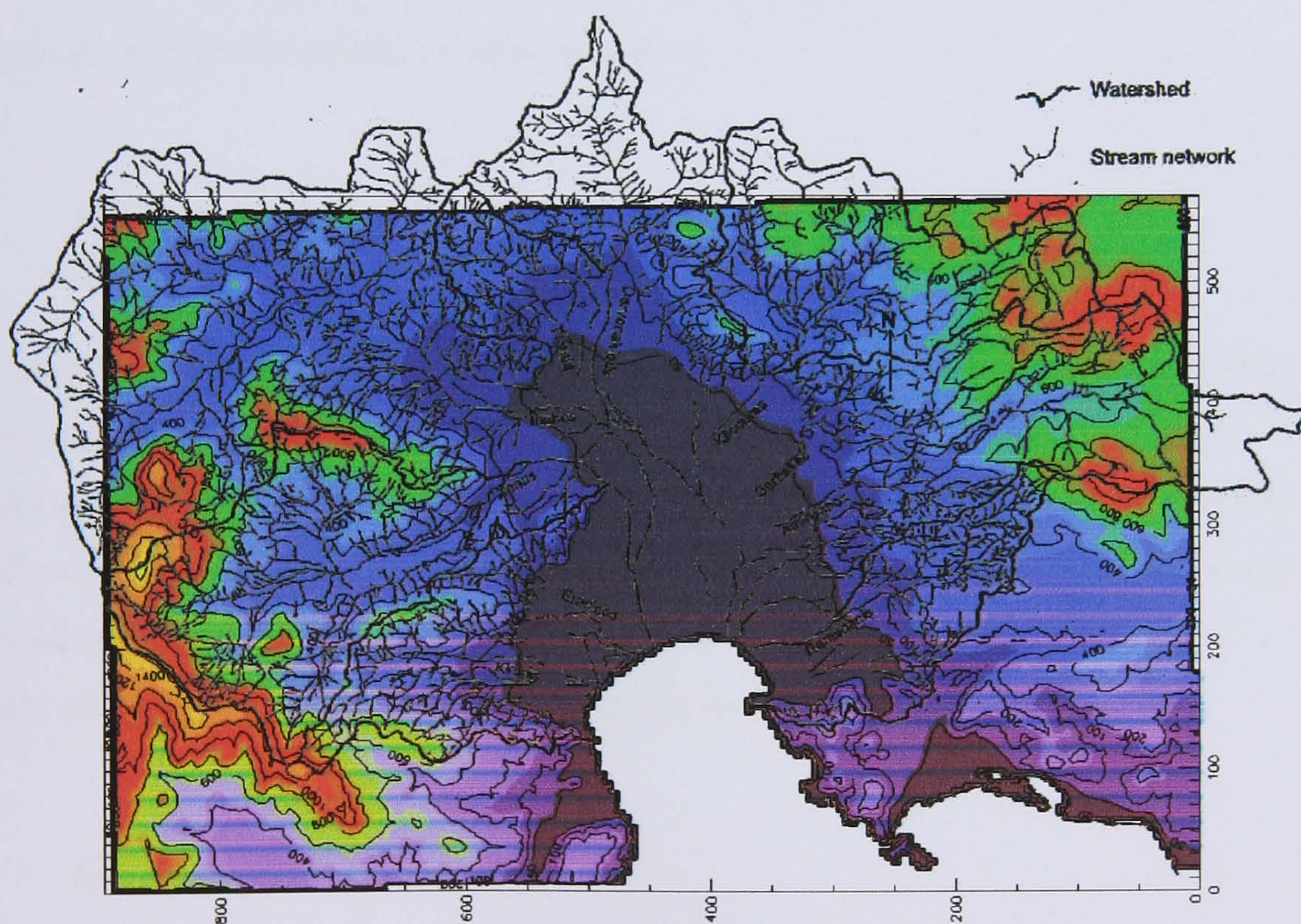
The topographic data for the Argolid (Hellenic Army Series, 1970) is shown again in Figure 4.2, with the boundary of the Argolid catchment and stream superimposed (Poulovassilis et al, 1994, p.13). It can be seen that the topographic data does not



extend to cover the whole of the catchment area. However, the area of the catchment that lies beyond the boundary of the topographic data is quite a small proportion of the total catchment area. Because it is at the periphery of the catchment, and it is assumed that there is no flow across the watershed, the topographic data will be treated as if it covers the whole of the catchment. Where the watershed lies beyond the topographic data, it will be assumed that the edge of the topographic data represents the edge of the catchment.

#### 4.1.7. Soils.

As stated in Chapter 1, the soil forms the physical interface between the environment and the human systems. Agriculture is based upon the fertility of the soil (either natural or artificially induced), buildings are constructed on (and indeed in) it, and it can be



**Figure 4.2 Topographic data for the Argolid valley (Hellenic Army Series, 1977) with watershed and stream network superimposed (Poulovassilie et al, 1994, p. 13).**



sold, so acquiring a market value. Physically soil is formed from the weathering of rock, by a variety of processes. However, the time scales over which soil formation processes operate are sufficiently long that they can be ignored in this thesis.

### **Soil erosion**

Soil erosion processes operate on a shorter time scale, and soil erosion is often a result of modern agricultural practices (Brady and Weil, 1996, p.563). However, for the same reason that river flows are so difficult to model, soil erosion processes are also difficult to model, because the erosive processes change the character of the domain (in this case the soil) upon which the erosive processes operate (co-evolution).

For the specific case of the Argolid, soil erosion is not perceived as a problem, particularly for the timescale over which the model operates. Therefore, erosive processes will not be included within the model.

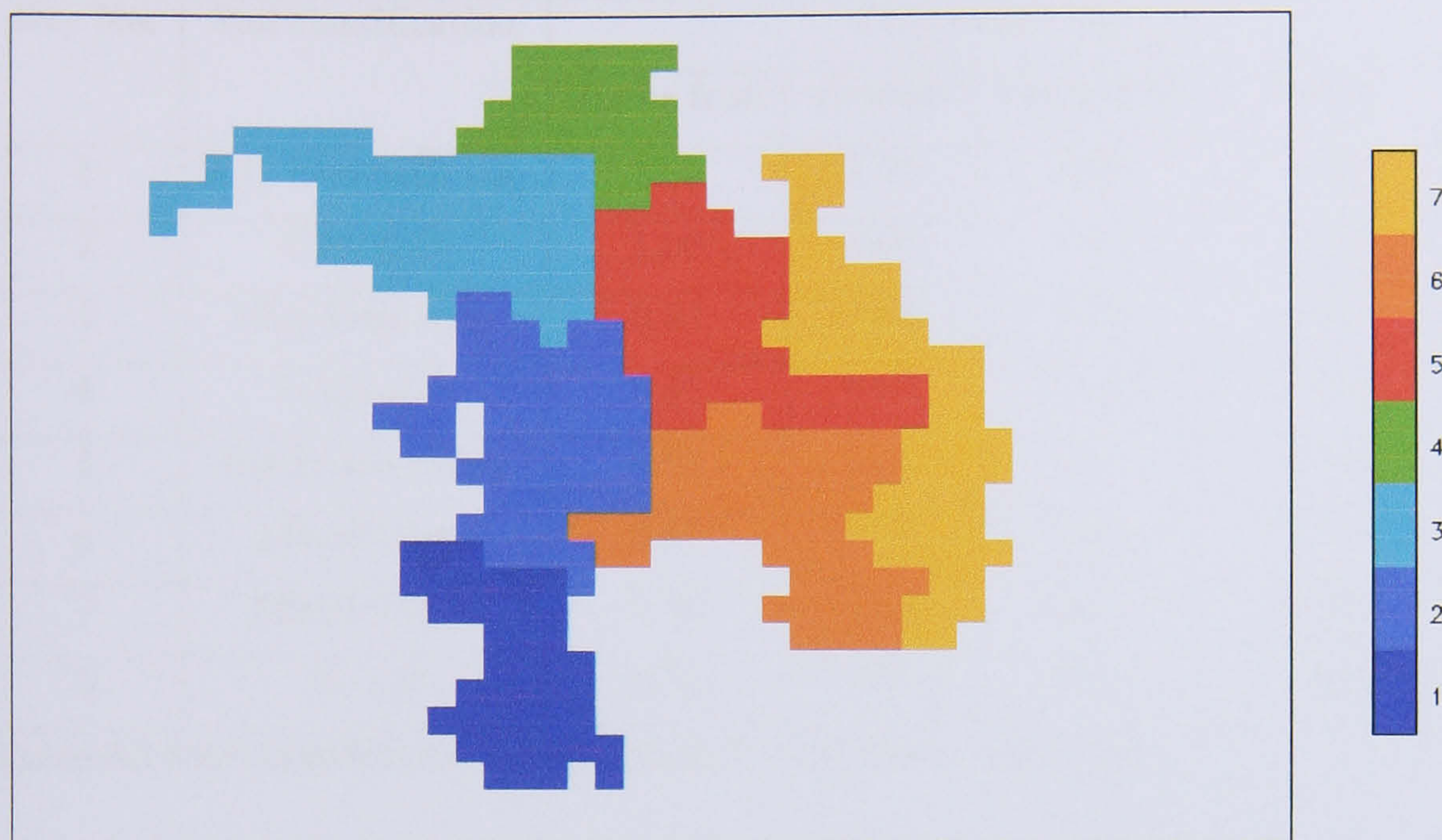
### **Water transport and storage**

Although, as indicated in Chapter 3, the flow of water through the soil does not occur under quite the same conditions as flow within the aquifer, the flow equations are essentially the same. Therefore, as stated above, the soil will be treated as another layer of the aquifer, albeit by definition the uppermost layer. The different flow and storage conditions that are found within the aquifer will be accounted for by changing the values of hydraulic conductivity and storativity in this layer.

### **Soil quality**

Soil quality is a term that incorporates a number of different factors and here refers to the suitability of a particular soil for the growth of a particular crop. The selection of crops is handled by the econometric model (section 4.3) derived from Allen et al. (1994,





**Figure 4.3 Distribution of soil types in the model. Key numbers refer to Table 4.2.**

Chapter 10), and therefore the soil types used within the model are taken from that analysis of agriculture in the Argolid. Figure 4.3 shows the distribution of different soil types used and Table 4.2 gives the suitability coefficients for the different crop types in the econometric model.

The econometric model uses the soil quality and suitability parameter in the calculation of crop production rates. In Allen et al. (1995) this parameter is invariant over time, and is classified spatially in to seven zones, with a unique value for each spatial (zone) and biological (crop type) combination. The different zones were defined largely by the geographical distribution of different soils (Allen, *pers. comm.*). Therefore, the different zones from Allen et al. (1995) will be used in the model to represent the suitability of the soil for the different crop types. Because the 7-zone model only covered the central plain (altitude less than 200m a.s.l.), obviously this dataset does not extend into the mountains. However it is apparent from the geological map (Figure 3.1) that there are only negligible amounts of soil in the mountains, confined to the vicinity of river beds. Therefore, the rest of the model domain will be classified as having zero soil suitability for all crop types (i.e. it is impossible to grow any crops in these regions).



Key No.	Soil classification	Crop suitability			
		Citrus fruit	Cereals	Vegetables	Olives
1	Silty loam/silty clay	1.00	1.00	1.00	1.00
2	Clay soils	1.00	1.00	1.00	1.00
3	Clay loam soils	0.85	0.88	0.72	0.98
4	Loam soils	0.67	0.72	0.44	0.96
5	Sandy loam soils	0.95	0.96	0.90	0.99
6	Mixed (clay)	0.95	0.96	0.90	0.99
7	Mixed (loam)	0.78	0.82	0.61	0.98
8	No soil	0.00	0.00	0.00	0.00

**Table 4.2 Soil classification and suitability for different crop types.**

#### 4.2. METEOROLOGY.

The atmosphere represents the upper sink/source of water for the water resource system (the lower sink/source being flow to/from an adjacent aquifer or the sea). The source process for water is precipitation in all its forms. The sink process is a combination of two separate processes. First there is evaporation of water either standing on the surface or from the top of the soil. The second is transpiration of water from plants. The two processes are very difficult to measure separately since both processes convert liquid water to water vapour and both occur in close proximity to each other. The combined processes are referred to as evapo-transpiration.

##### 4.2.1. *Precipitation.*

The atmospheric processes involved in the production of precipitation are beyond the scope of this thesis. However, there are several characteristics of precipitation that are important to water resources, specifically the coverage, duration, intensity and character (rain/snow) of precipitation events as well as the spatial and temporal frequency. These



characteristics essentially control the surface flow of water (as mentioned in the previous section), which in turn controls the amount of inflow to the aquifer. Thus while it is not possible to model the actual processes in this thesis, it will be possible to reproduce the characteristics of precipitation in the Argolid, so as to have accurate moisture input to the rest of the model.

### **Temporal variability**

There are two different time scales of temporal variability, which are important to consider within the model. The larger scale is the annual variation in precipitation, both in terms of seasonal (sub-annual) and inter-annual variation. The smaller scale is the daily and sub-daily variation in precipitation that is associated with the passage of distinct (discrete) precipitation events.

#### *Annual scale*

The variation in climate from year to year is very hard to predict, and is subject to distinct and varying trends at global and regional levels (Adler, 1999). Therefore, the model will use two possible ways of calculating annual precipitation. The first is a stochastic variation in the average annual precipitation:

$$A_n = 2A_o(1 - r)$$

where:

$A_n$  = average annual precipitation in year  $n$ ;

$A_o$  = average historical annual precipitation;

$r$  = random number between 0 and 1.

However, this will not be of use when attempting to calibrate the model, so the historical variation in annual rainfall will also be included. Figure 4.4 shows the variation in average annual precipitation generated by the above equation and the

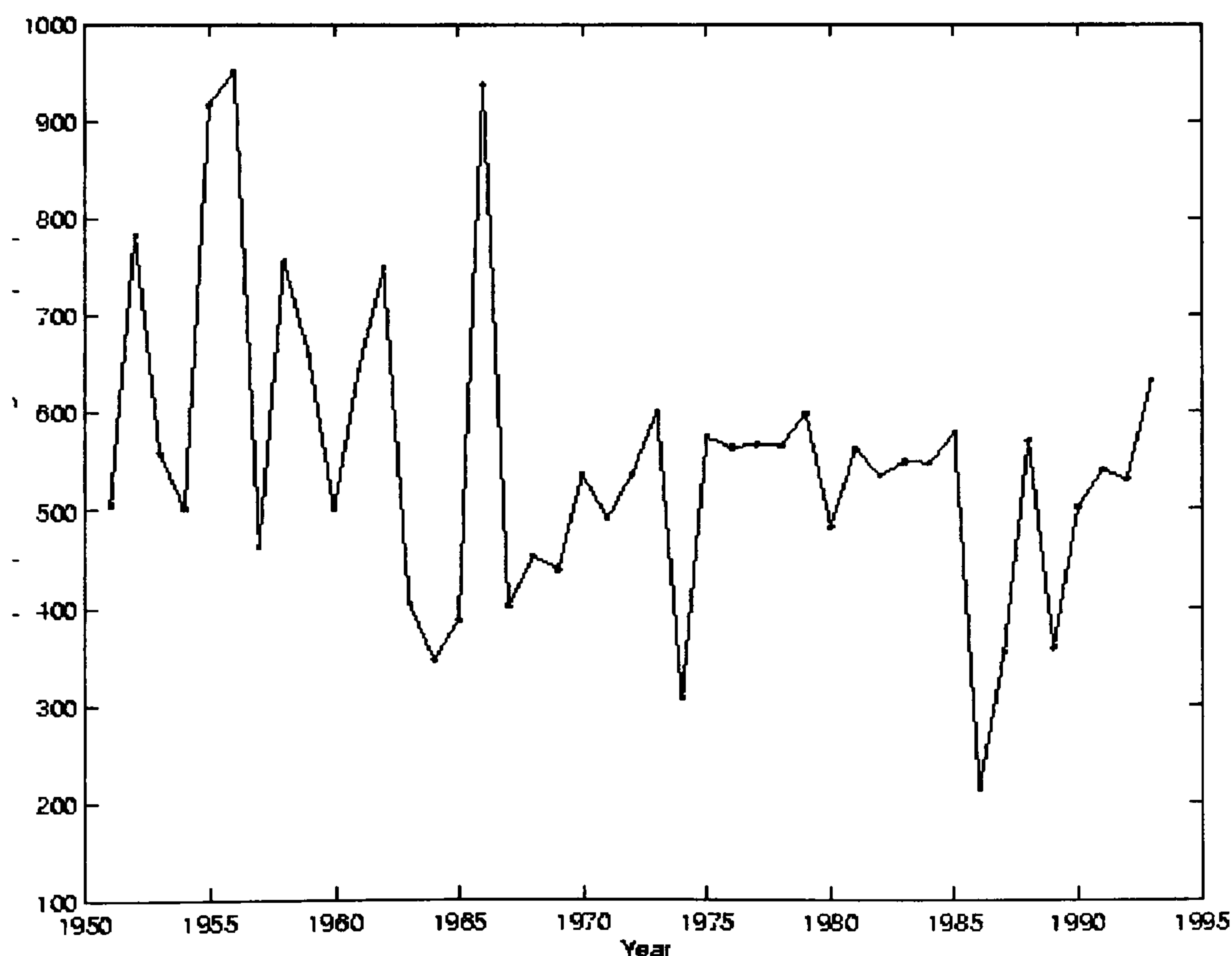


frequency distribution of precipitation events generated within the model compared to daily rainfall data for Argos meteorological station.

It can be seen from Figure 4.3, that while the annual rainfall was above average in the 1950's, it was average or below average in the 1970's and 1980's, with particularly low rainfall in 1986 and 1988. Because of this a distinct trend of decreasing annual precipitation can be seen for the 40-year period from 1950 to 1990.

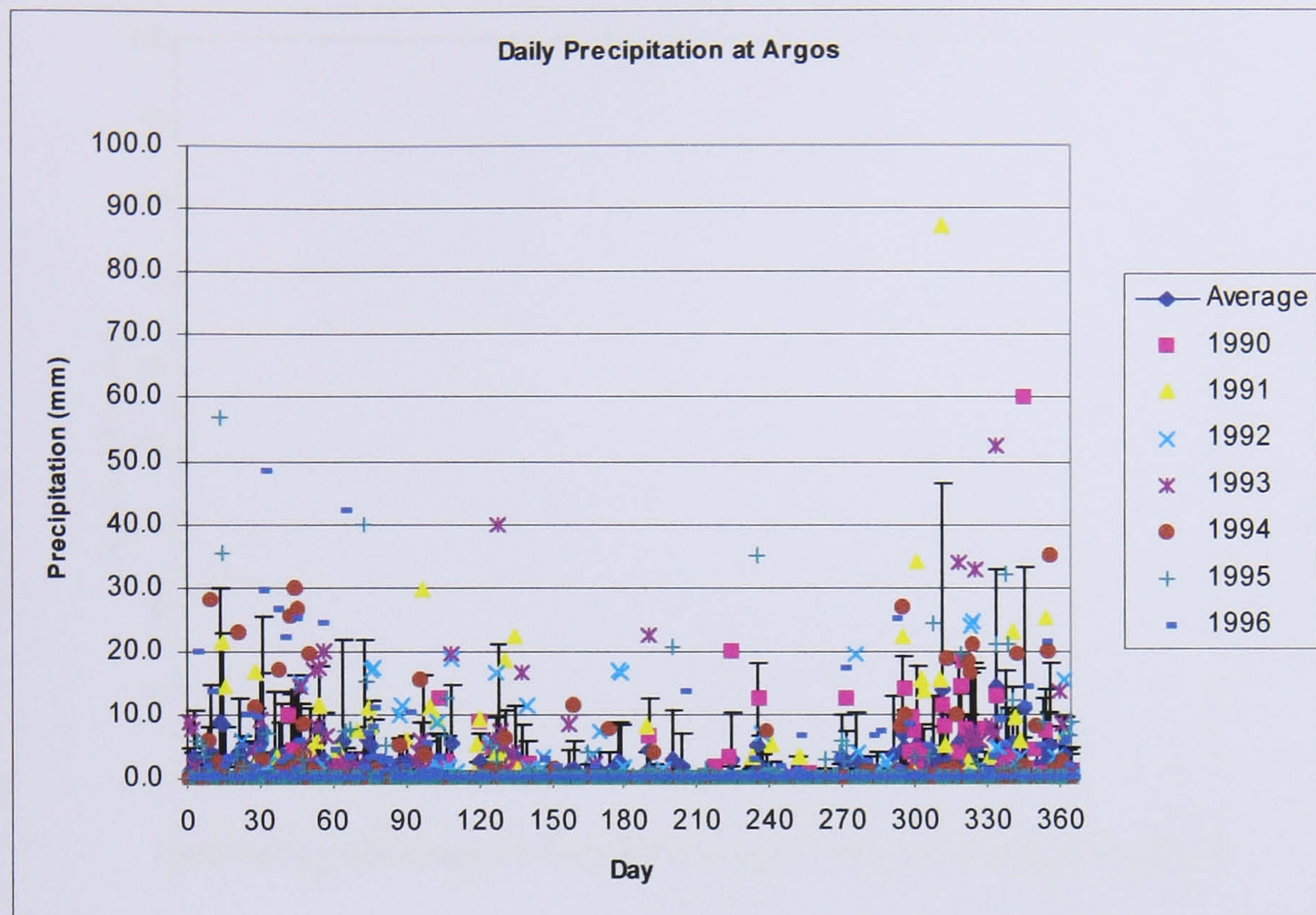
### *Diurnal scale*

While the annual precipitation is of general importance, it is the amount of rainfall on a daily basis that affects the farmers' requirement for water. Therefore, the model must include the variation in precipitation from day to day. Unfortunately, the diurnal meteorological data for the Argolid Valley is restricted to a short time series of daily



**Figure 4.4 Historical variation in annual precipitation in the Argolid Valley. Vertical scale is annual precipitation in millimetres.**





**Figure 4.5** Daily precipitation at Argos.

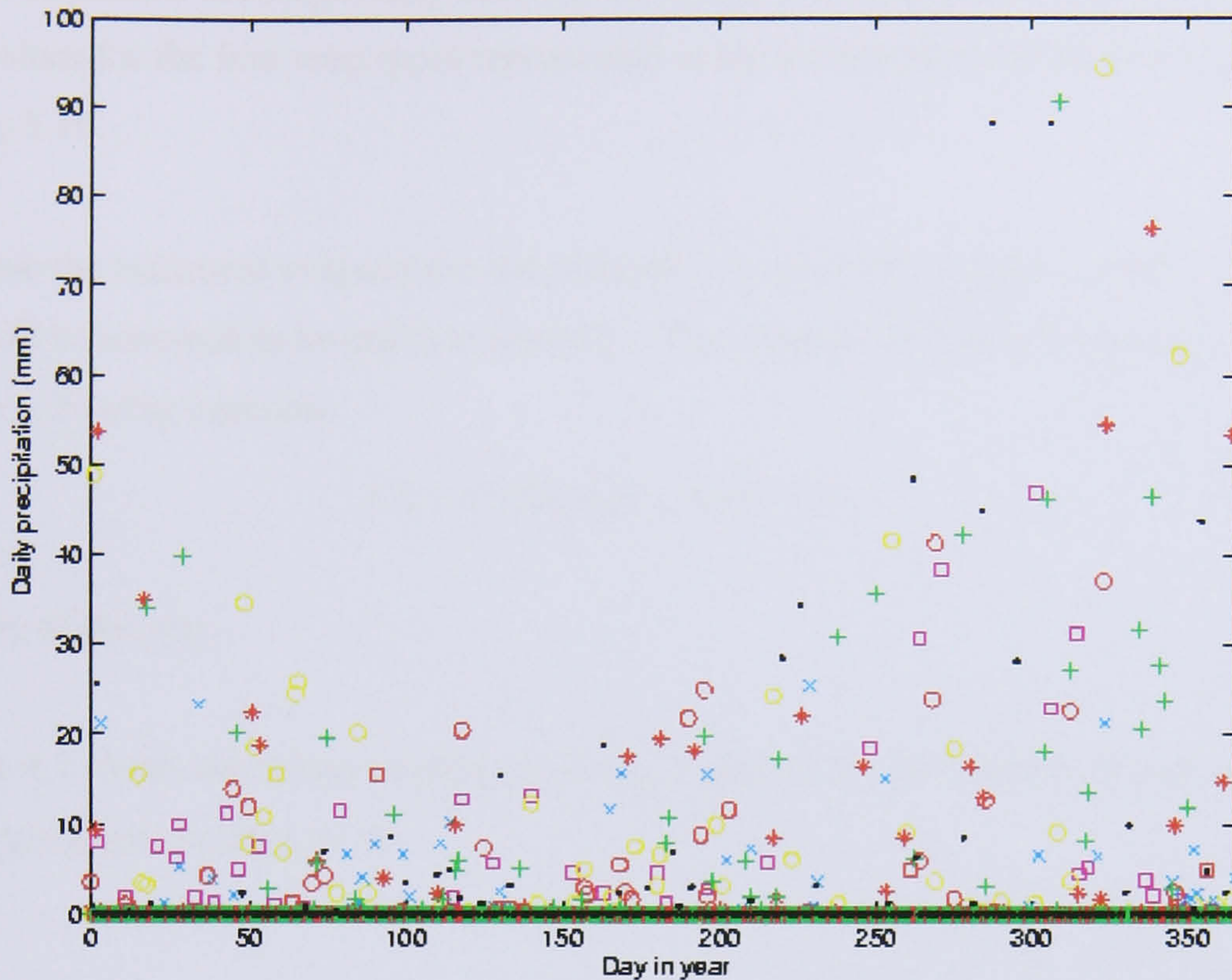
precipitation data from the meteorological station at Argos. This time series provides can be used to provide an approximate frequency distribution of daily rainfall throughout the year. Figure 4.5 shows the distribution of daily rainfall from the historical data.

Figure 4.6 shows a frequency distribution generated from a uniform random distribution, covering a similar length of time to the historical data. The sum of the generated daily precipitation is modified by the actual annual precipitation, so that the total precipitation in each year matches the historical data.

#### 4.2.2. *Evapo-transpiration*

Evaporation and transpiration are both processes whereby moisture is transmitted to the atmosphere. Because it is very difficult to measure transpiration in the absence of evaporation, it is normal to consider the two processes together, as evapo-transpiration.





**Figure 4.6 Modelled daily precipitation for same 7 year period as Figure 4.5.**

The driving force for both processes is solar heating, and therefore evapo-transpiration varies both during diurnally and annually.

Knowledge of evapo-transpiration is important in agriculture because it is an important factor in deciding when (and whether) to irrigate a crop. There are a variety of methods for calculating evapo-transpiration which differ in the type of data they require (Shaw, 1983, p.267; Schwab et al., 1993, p.58). Because there are actual pan evaporation rate measurements for the Argolid, the simplest method can be used to calculate a crop evapo-transpiration rate:

where:

$$ET_{crop} = k_c ET_0$$

$ET_{crop}$  = crop evapo-transpiration rate;

$ET_0$  = measured evaporation rate;

$k_c$  = crop coefficient.



Crop coefficients are empirically derived, for example in Doorenbos and Pruitt (1977). The values for the four crop types represented in the econometric model were shown in Figure 3.10.

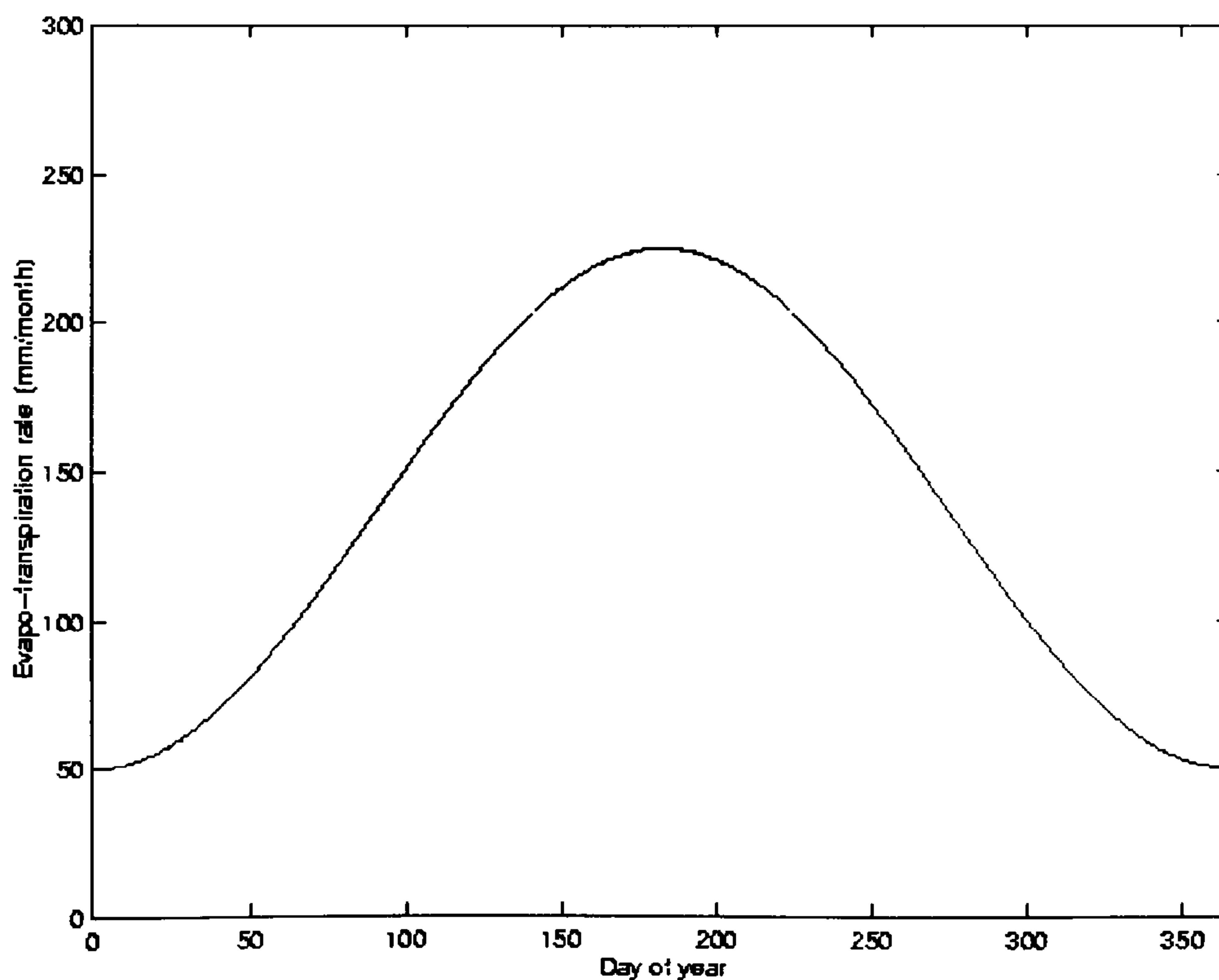
Because the measured evaporation data (Figure 3.8) showed negligible spatial variation,  $ET_0$  will be assumed to be uniform spatially. The temporal variation will be generated by the following function:

$$ET_0 = 175(\sin(\pi d / 365))^2 + 50$$

where:

$d$  = day of the year.

Figure 4.7 shows the evapo-transpiration rate produced by this formula, which is very close to the data in Figure 3.9.



**Figure 4.7 Modelled evapo-transpiration rate,  $ET_0$ .**



#### 4.2.3. Temperature

The amelioration of frost by the use of sprinkler irrigation systems is a significant use of groundwater. As described in section 3.2.3, frost occurs more frequently in the interior of the Argolid Valley, and less frequently at the coast. This is represented in the model by relating the occurrence of frost to temperature and altitude. Frost is assumed to occur on days when the daily temperature falls below a specific value (approximately 0°C). Unfortunately, there is no accurate data on the diurnal temperature variations in the Argolid. Therefore, the normalised daily temperature is described by applying a random distribution to a sinusoidal function:

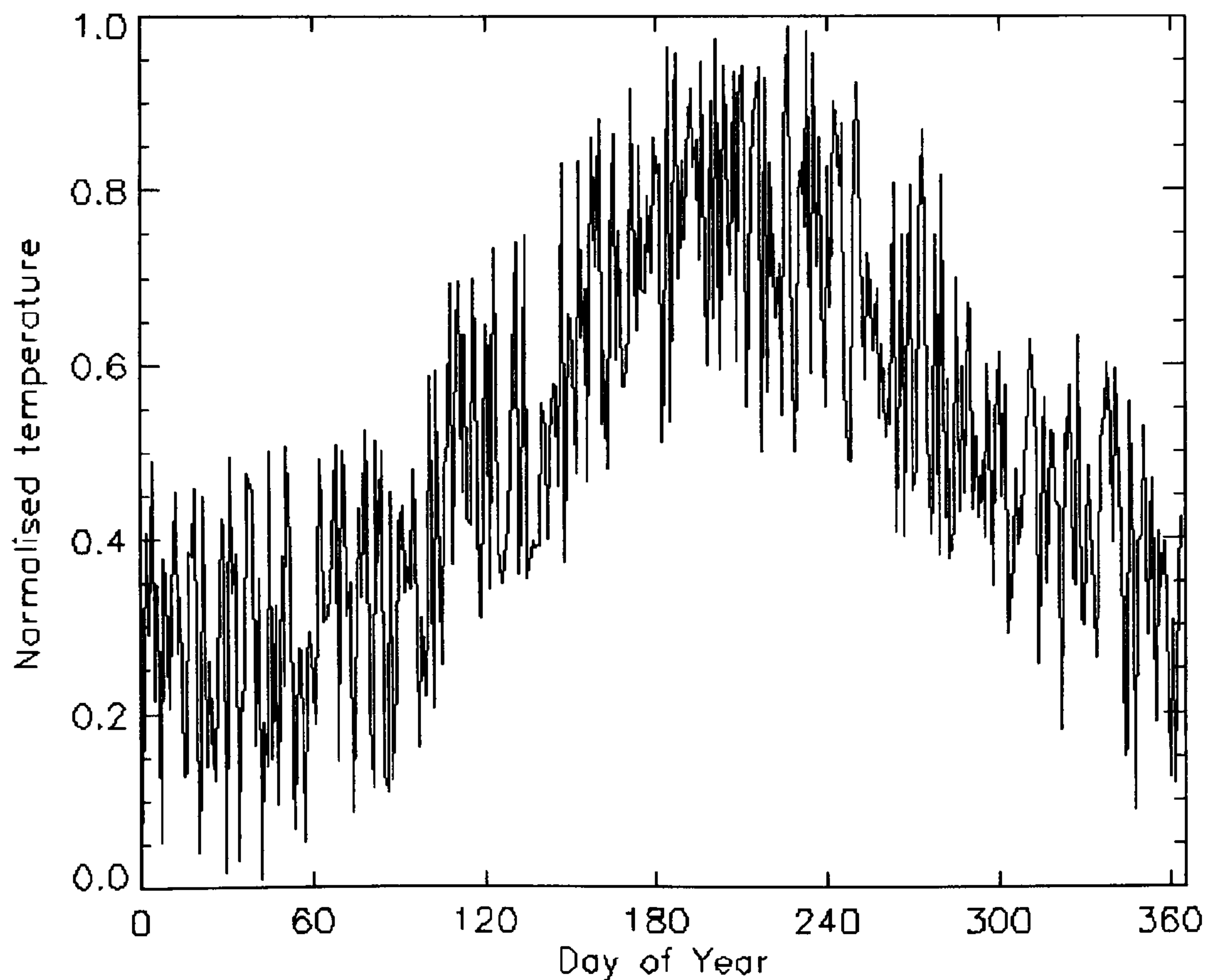
where:

$$T_d = \sin(\pi(d - 30)/365)^2 + r$$

$T_d$  = daily temperature;

$d$  = day of year;

$r$  = random number.



**Figure 4.8 Example of normalised temperature range used in model.**



An example of these normalised daily temperatures can be seen in Figure 4.8. Frost occurs when the daily temperature falls below a level specified by the following function:

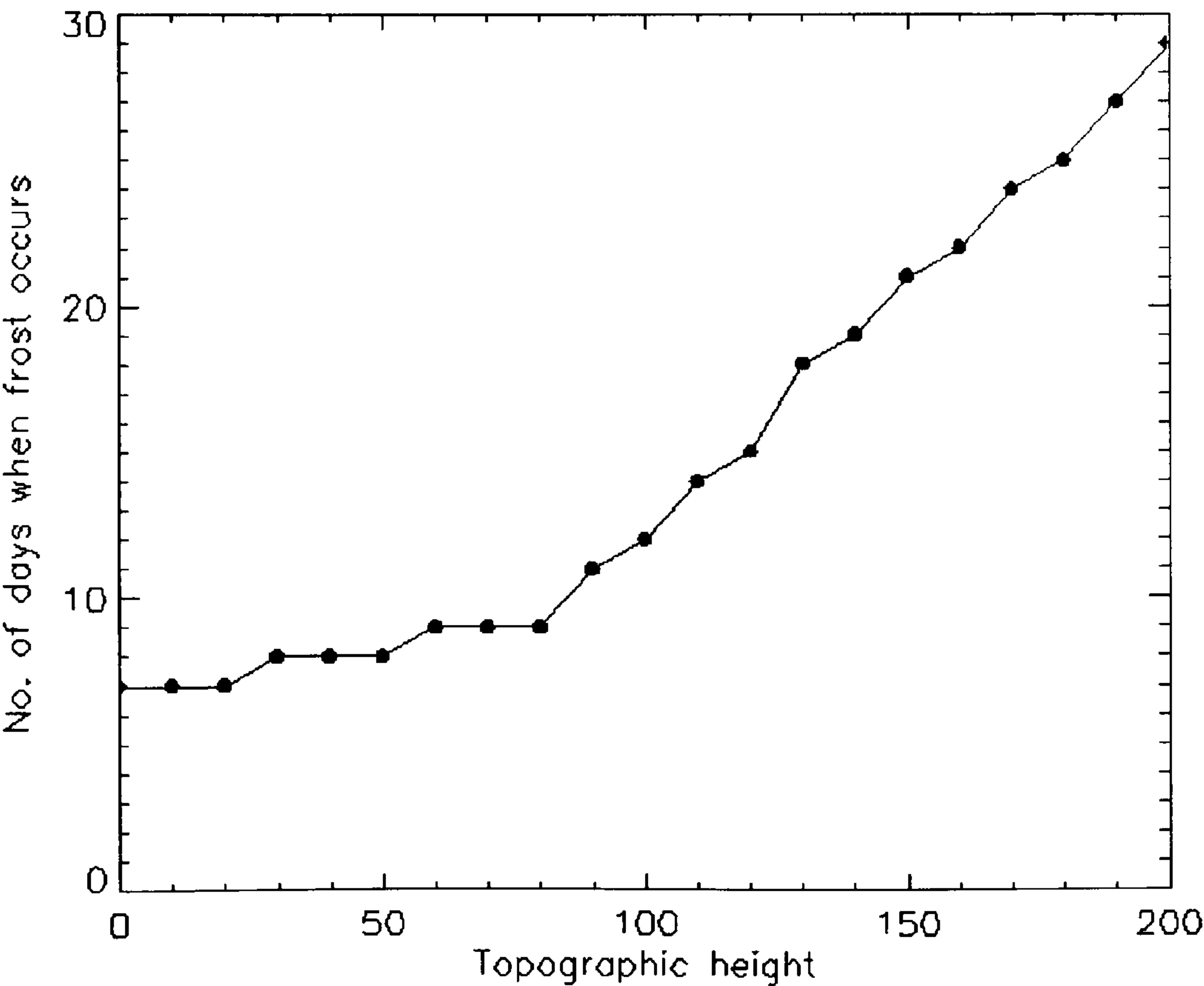
$$f = c_f - (200 - h_s)/2000$$

where:

$c_f$  = a constant;

$h_s$  = topographic height.

For the Argolid Valley,  $c_f = 0.15$  adequately describes the variation in the frequency of frosts. Figure 4.9 shows how the above functions produce a variation in the occurrence of frost with topographic height.



**Figure 4.9 Modelled relation between occurrence of frost and topographic height in the Argolid Valley.**



### 4.3. ECONOMY

The economic part of the model is solely concerned with agriculture, because this sector is the largest user of water in the Argolid Valley, with ~85% of water used in the area being used for agricultural irrigation (Allen et al., 1995). The economic processes implemented here are derived from the econometric model described in Allen et al, 1995, Chapter 10), so only a brief description of this model will be given here.

The econometric model essentially reproduces the outcome of the decision making process that farmers go through in deciding which crops to grow, and how much land area to dedicate to each crop.

#### 4.3.1. *Crop profitability*

Crop profitability is a function of the price a crop can be sold for, the costs associated with producing the crop, and the amount (mass) of crop that can be produced on a given area of land.

#### **Costs**

The only costs included in the model are a constant, crop dependent cost, and the costs associated with irrigation. The crop dependent cost is assumed to include all the normal production costs associated with each crop, such as labour, fertilisers, pesticides etc. The irrigation costs are related to the costs of extracting groundwater, such as borehole maintenance and the energy to extract water from the aquifer. They are combined in the model in a single crop-cost function:

$$C'_{Total} = c_i + p_i c_w d_i (h_h^0 / h_h^t)$$

where:

$C'_{Total}$  = total crop production costs at time t per unit area;

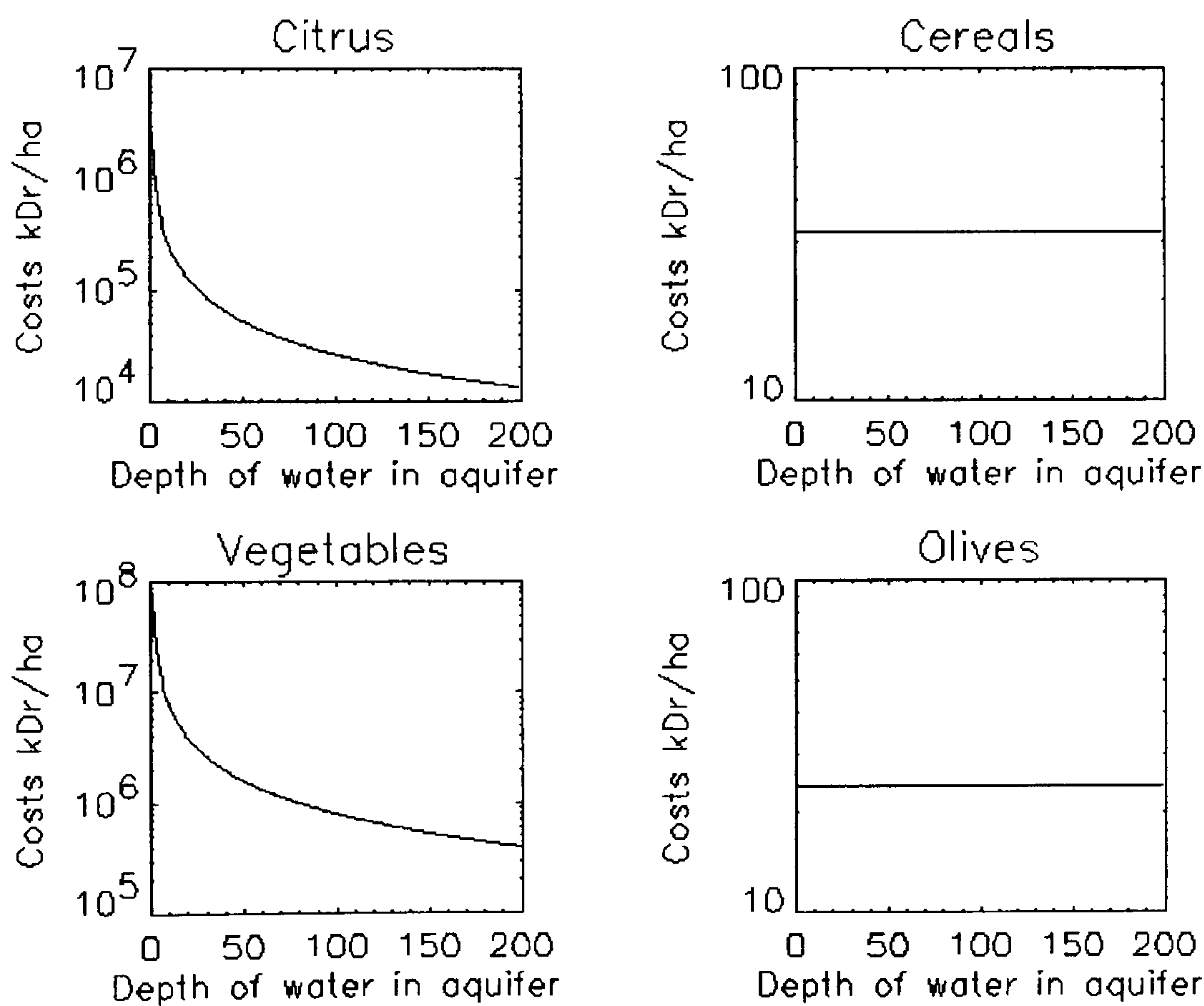
$c_i$  = constant costs associated with each crop;

$p_i$  = perfect rate of production of crop c in kg/ha;



$c_w$  = cost of water use in litres/Drachma;  
 $d_i$  = water requirements of crop c for maximum production;  
 $h_h^0$  = level of water in aquifer at time  $t = 0$ ;  
 $h_h^t$  = level of water in aquifer at time  $t$ .

Figure 4.10 shows example variations in cost with depth of water in the aquifer, assuming an initial depth of water in the aquifer of 200m. The production costs of cereals and olives do not vary with depth because these crops are assumed to not require irrigation.



**Figure 4.10** Example of variation of modelled production costs with depth of water in the aquifer.



## Production

The production of a modelled crop can be reduced below the perfect production level in by two ways. The first is due to the salinity of the irrigation water, and the second is due to a shortfall in meeting the crop water requirements.

### *Salinity*

Each crop has a parameter specifying its resistance to salinity. This parameter and the modelled salinity of water in the soil/surface layer are used to generate a reduction in production:

$$R_s = 1 - a.r_s.S_c$$

where:

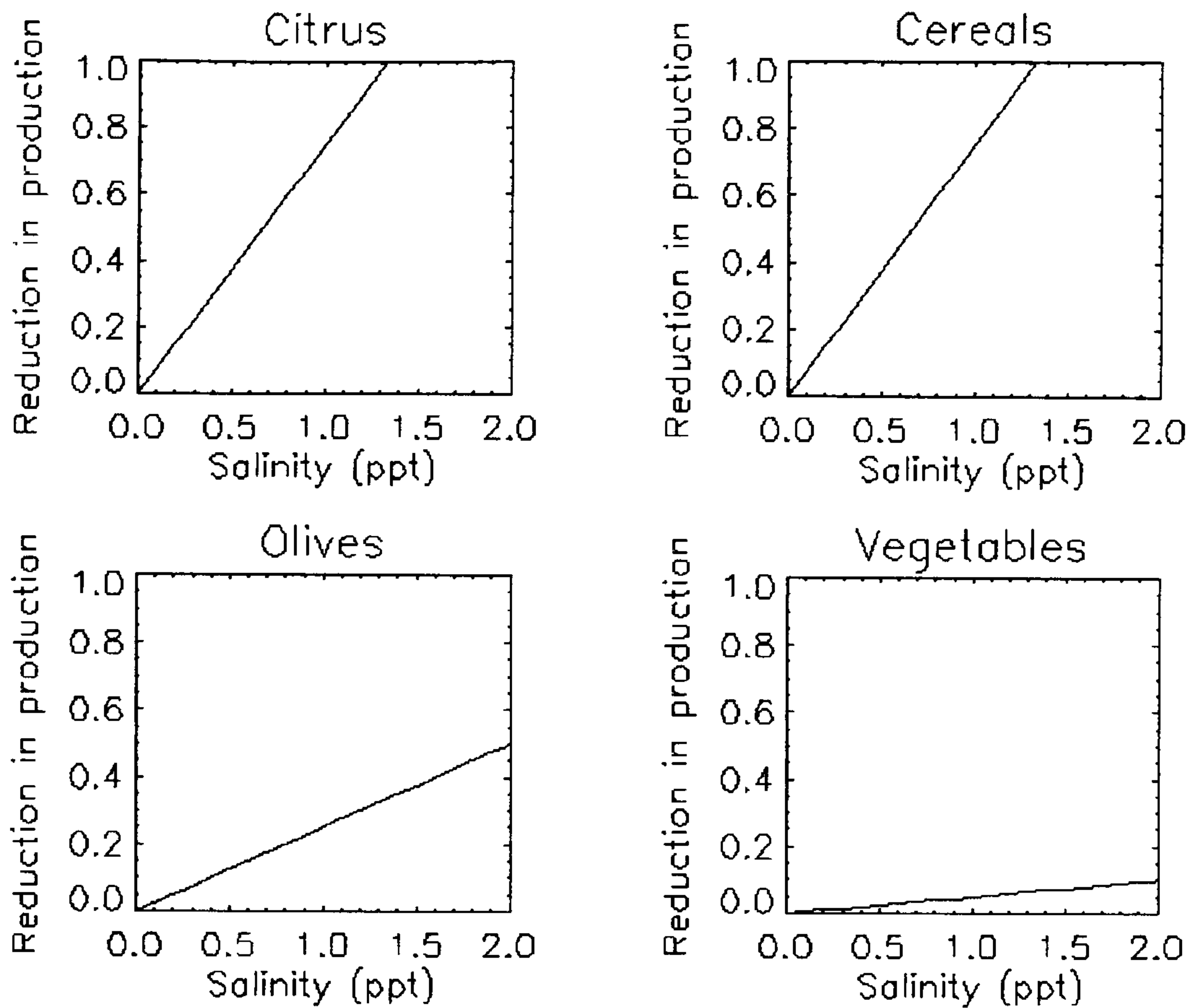
$a$  = a constant, equal to 0.5 when salinity is in units of ppt;

$r_s$  = resistance to salinity parameter for a given crop;

$S_c$  = salinity concentration in ppt.

The proportionate reduction in production that this function generates are shown in Figure 4.11. It can be seen that citrus crops and cereals are the most susceptible to salinity, while vegetables are highly resilient.





**Figure 4.11 Reduction in production due to salinity for the four crop types.**

### *Water shortage*

An insufficient supply of water to a crop may lead to reductions in the level of production, particularly if the shortfall coincides with critical stages in the crops development (Forbes and Watson, 1992, p.278). However, these effects vary greatly between plant species and therefore the model uses a very simple empirical function to represent some of the reduction in crop productivity that will result from a water shortage:

$$R_w = (S_z/V_z)^{0.15}$$

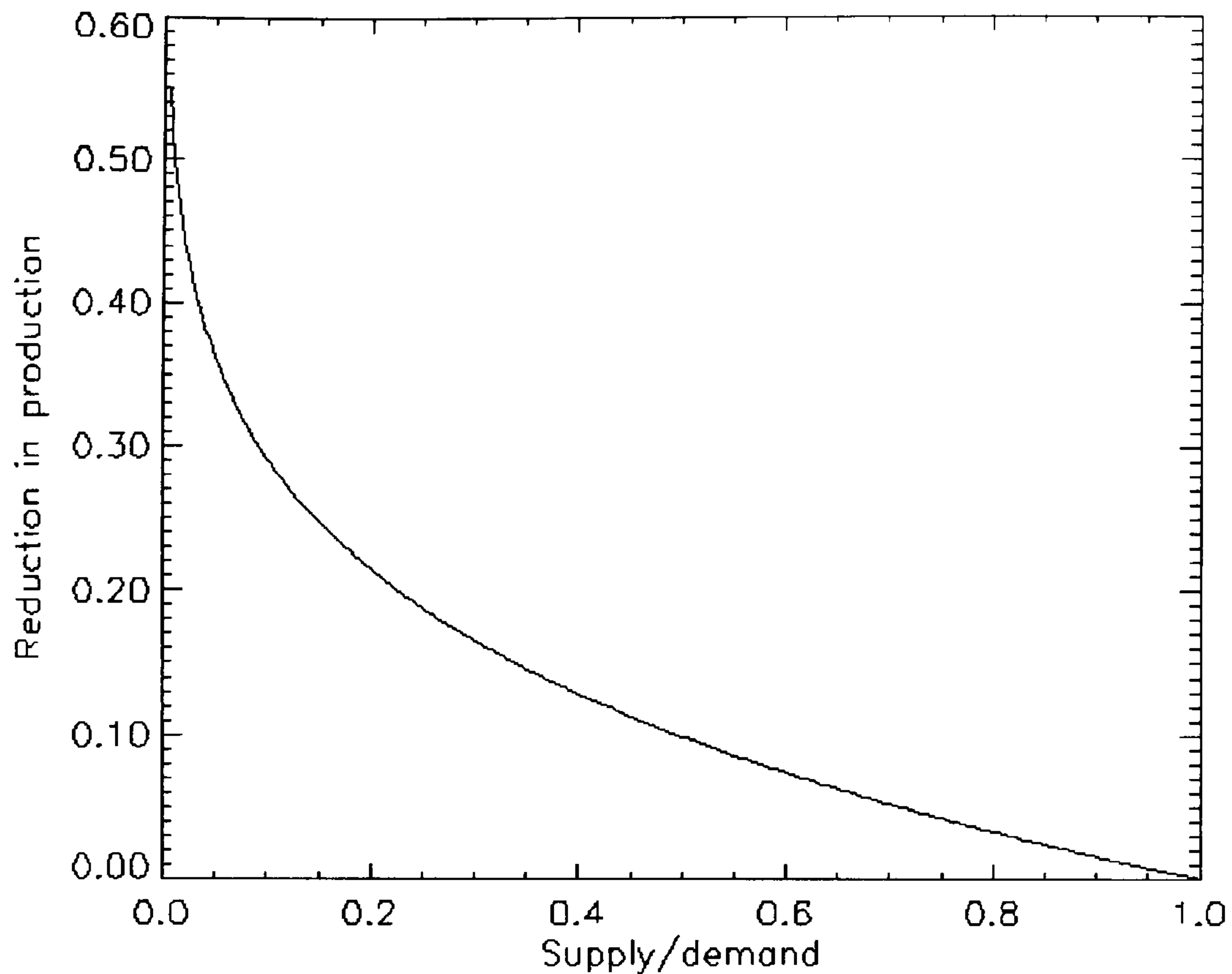
where:

$R_w$  = reduction in production due to water shortage;

$S$  = supply of water in cell  $z$ ;

$V$  = demand for water in cell  $z$ .





**Figure 4.12 Reduction in production due to water shortage.**

Figure 4.12 shows the reduction in production due to water shortfall. In the model, this reduction only applies to the crops that require irrigation: citrus fruits and vegetables. These crops require large amounts of water, and in practice farmers in the Argolid Valley do not irrigate the other crop types. It can be seen that even with no irrigation, there will still be some production.

### *Actual production*

The actual production that is achieved is assumed to be the perfect production level, minus all reductions in production due to salinity, water shortages, or the suitability of the soil:

$$P_a = P_p R_o R_s R_w$$



where:

$P_a$  = actual production (kg/ha);

$P_p$  = perfect production (kg/ha);

$R_o$  = reduction in production due to soil suitability;

$R_s$  = reduction in production due to salinity;

$R_w$  = reduction in production due to water shortages.

The important point to note about actual achieved production is that the reductions to production are cumulative, which can result in very low production levels when both quantity and quality of water in the aquifer are impaired.

### **Profitability**

The actual profitability of a crop varies temporally and spatially according to the product of actual production that is achieved, the price paid for the crop, and the costs:

$$Profit = P_a r - C_{Total}$$

where:

$r$  = price paid for the crop (Dr/ha);

other terms as described above.

Because costs are calculated using the perfect production levels, it is quite possible for large losses to be incurred by the farmer. However, implicit in the model is the assumption that all losses are written off or offset by some outside agency, for example through the operation of the Greek government, or the Common Agricultural Policy.

#### *4.3.2. Land allocation*

Once the profitability of each crop has been calculated, a proportion of the available growing area can be allocated to each crop. The model calculates a desired distribution of crop types, which is the farmers ideal, but the farmers are prevented from changing



more than a small proportion of the land area from one crop to another. This is because in practice farmers do not switch large areas of land between crops, because of the costs of doing this (which are not considered in the model), except in exceptional circumstances (Allen et al., 1995).

The desired proportion of agricultural land devoted to each crop is calculated as follows:

$$D_{c,i} = \frac{e^{bP_{c,i}}}{\sum_c e^{bP_{c,i}}}$$

where:

$D_{c,i}$  = desired area of land in cell  $i$  allocated to crop  $c$ ;

$P_{c,i}$  = profitability of crop  $c$  in cell  $i$  ;

$b$  = farmer rationality, equal to 0.03 in Allen et al. (1995).

The actual area of land then allocated to each crop for the coming year is then:

$$A_{c,i}^t = A_{c,i}^{t-1} - \Delta A_{c,i}$$

where:

$A_{c,i}^t$  = land area in cell  $i$ , allocated to crop  $c$ , for year  $t$ ;

$A_{c,i}^{t-1}$  = land area in cell  $i$ , allocated to crop  $c$ , for year  $t-1$ ;

$\Delta A_{c,i} = (D_{c,i} - A_{c,i}^{t-1})/20$  .

The apparently low value of the farmer rationality parameter,  $b$ , indicates that the farmers do not use profitability as their sole guide to crop choice. Rather they also probably use factors such as risk, to avoid being too reliant on any one crop for their income.



#### 4.4. THE MODEL STRUCTURE.

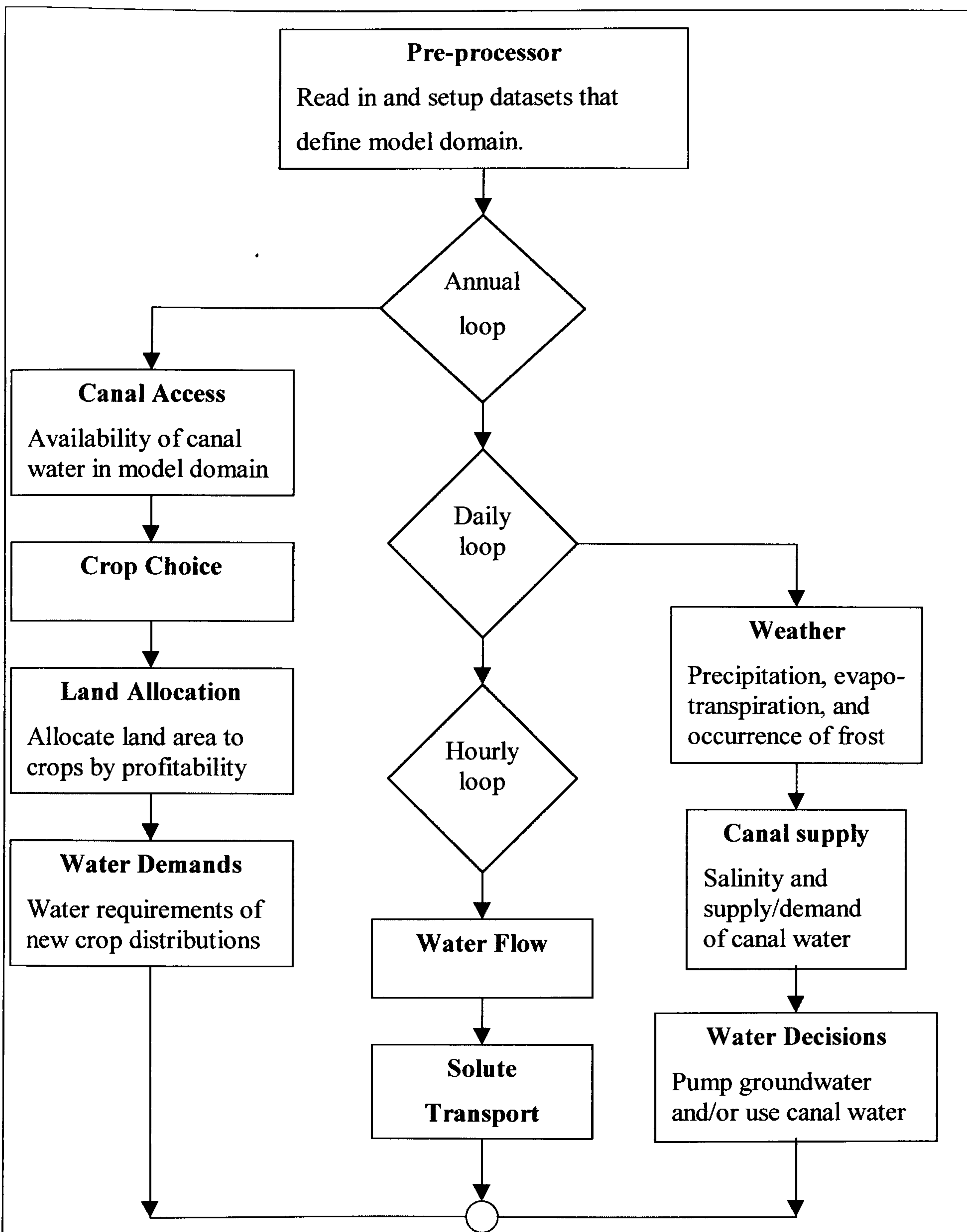
The model structure is shown in Figure 4.13. It can be seen that there are three separate temporal loops in the model. The hydrogeological model of water flow and solute transport in the aquifer operates on a sub-diurnal time scale, while the econometric model (as represented by the subroutines **Crop Choice** and **Land Allocation** in Figure 4.13) operates on an annual scale. The exogenous processes associated with climate and infrastructure development operate on both diurnal and annual scales. The interface between the hydrogeology and the economy takes place in the **Water Demands** and **Water Decisions** subroutines. As in Allen et al., (1995) this reproduces the apparent decision making behaviour of the farmers, in that the quantity and quality of water available affects their choice of crop, but on a day to day basis they attempt to meet the water requirements of their current crop distribution. The hourly loop that is specified for **Water Flow** and **Solute Transport** is necessary for numerical stability. The actual length of the timestep in the Hourly loop may be less than one hour or up to one day, depending on the grid size being used.

##### 4.4.1. *Model domain*

The model domain takes the form of a regular grid of cells, of specific size, with water heights and solute concentrations being calculated at the centres of cells, and volumetric flow being calculated at cell boundaries. Figure 4.14 shows a schematic representation of the calculations that are carried out in each cell. The aquifer can consist of a number of different layers, though due to the amount (lack) of geological data available for the Argolid valley only a single, vertically unconfined aquifer is used.

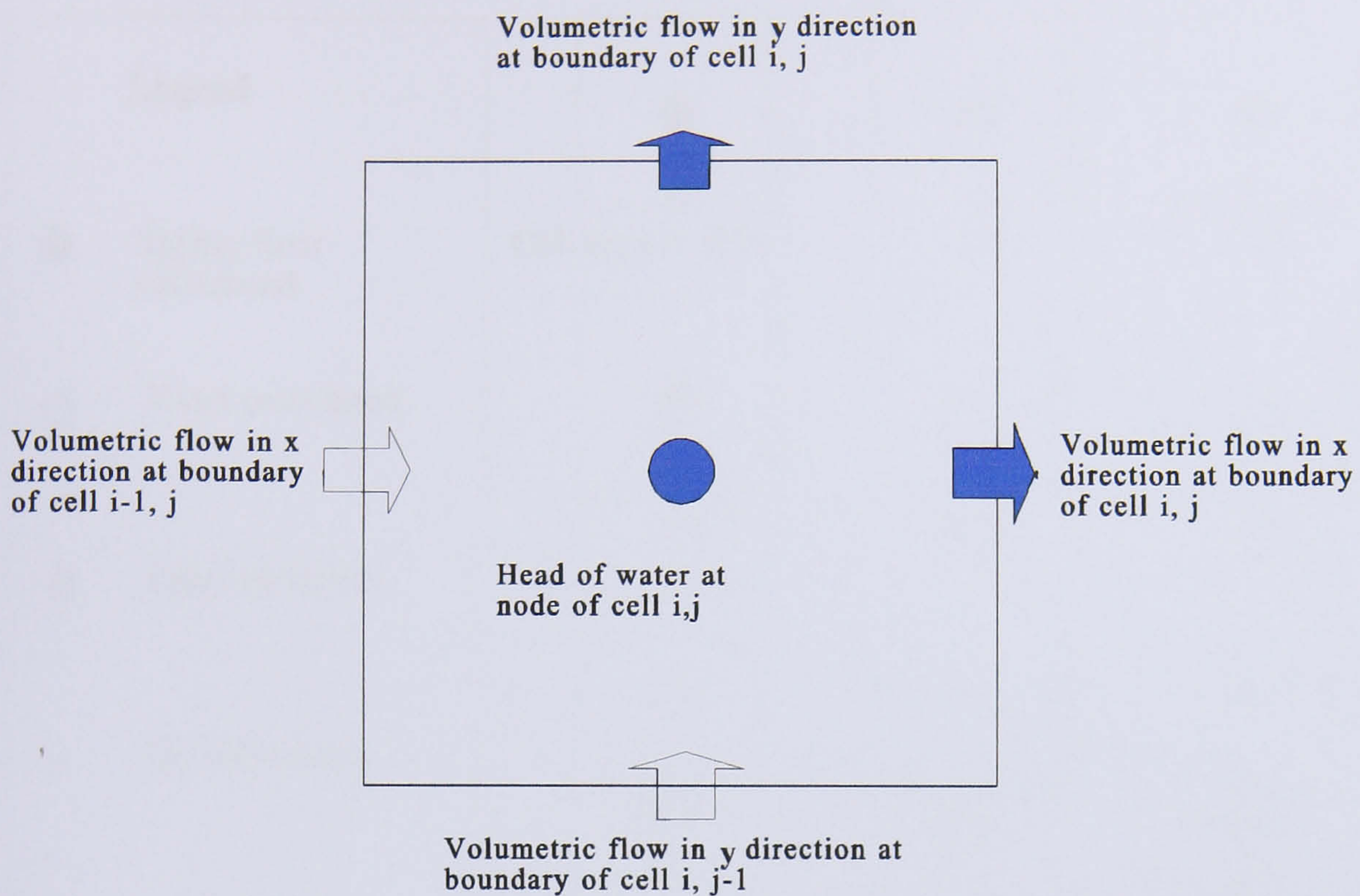
Each location within the aquifer is categorised. The categorisation takes the form of classifying each cell within the model domain, as being of a particular type, based on the calculations that will be performed at that cell. Each cell is given a four digit number with each digit representing the type of calculations that will be performed for





**Figure 4.13 Structure of sub-routines within the water resource system model.**





**Figure 4.14** A schematic representation of the flows calculated for any given cell in the aquifer.

springs (flow between model layers), water head, water flow in the x-direction, and water flow in the y-direction. Figure 4.15 demonstrates this classification scheme.

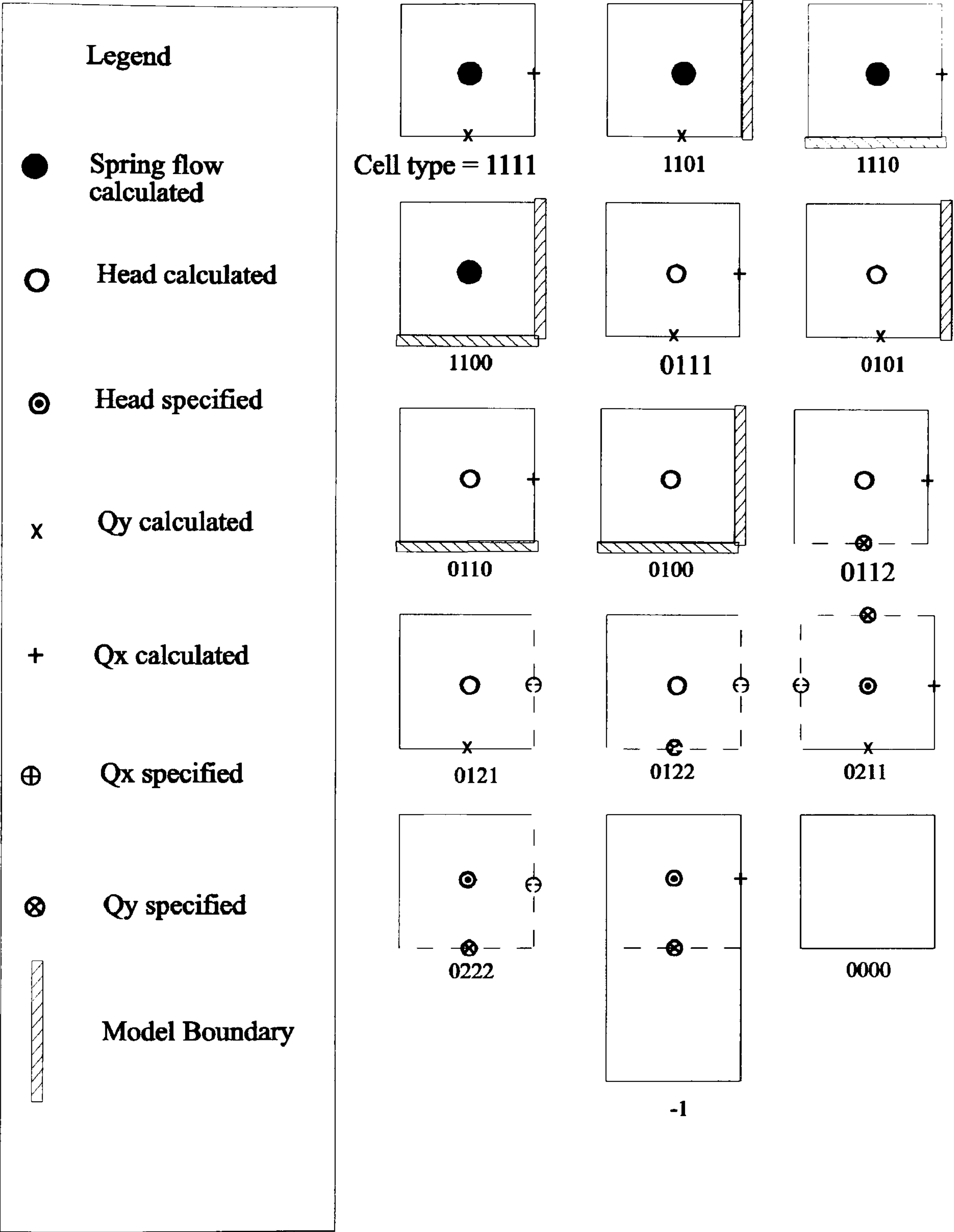
The value that each digit can take and the conditions that they represent are:

- (i) 0 = No calculation;
- (ii) 1 = Normal calculation;
- (iii) 2 = Value specified and constant.

The sole purpose of this classification scheme is to simplify the numerical computations that are carried out in the hydrogeological model.

The domain of the hydrogeological model consists of a series of specified datasets that define, at each cell (grid node): topographic height, height of aquifer base, hydraulic conductivity, storativity, initial water height and initial salt concentration. These datasets are invariant during the model run. In addition, each cell is specified as being





**Figure 4.15 Classification of cells according to calculations that the model will carry out at each grid cell.**



either within the model, outside the model, or on the boundary of the model. The model boundary on land is specified as being "no flow", which assumes that the aquifer catchment is the same as the surface catchment. This assumption would be realistic under equilibrium conditions but may be a source of error when the aquifer system is far from equilibrium. For example if the water level within the aquifer were greatly lowered, there would be an effective expansion of the aquifer catchment. The model boundary with the sea is "height specified" in that, flows to and from the sea can occur, but sea level remains invariant. In addition, the boundary with the sea is the sole source of solute (salt) currently included in the model.

#### 4.4.2. *Scale and Stability*

The timestep that must be used within the hydrogeological model is defined by the conditions for numerical stability. It may be necessary to use a smaller timestep if much smaller grid sizes are used. The stability criterion is that for transient flows in an unconfined aquifer with Dupuit assumptions (Wang and Anderson, 1982, p.87):

$$K\sqrt{Q}\frac{\Delta t}{S_s\Delta x\Delta y} \gg 1$$

where:

$K$  = hydraulic conductivity;

$Q$  = volumetric flow;

$\Delta t$  = timestep;

$\Delta x$  = grid size in the x direction;

$\Delta y$  = grid size in the y direction.

This criterion states that each cell must be independent (of adjacent cells) within a given timestep. Thus if a grid size is used whereby the flow distance (flow velocity multiplied by timestep) is greater than the grid size, then the computation will not be stable.



Simple calculations based upon expected values for the above parameters indicate that a timestep of 1 day would require the grid size to be greater than ~800m, while a timestep of 1 hour would require a grid size of greater than ~300m. Because of practical considerations such as computational time and the amount of data the model will generate, a grid size of 1 km and a timestep of 24 hours will be used as the smallest scale within the model. Therefore the smallest timestep used within the model, as it is applied to the Argolid will normally be 24 hours, and the model will have a regular grid with a grid size of 1 km.

#### 4.5. SUMMARY

In this chapter I have outlined the processes and structure which form the model. The model may easily be split into two parts, the physical environment and the economy. For both parts there are endogenous and exogenous processes, as well as processes which are excluded from the model. In the physical environment, the flow of water and the transport of solutes are endogenous, while atmospheric processes of precipitation, evapo-transpiration and frost are exogenous. Pedological processes are excluded from the model on the basis of the long timescale over which these processes operate and the numerical difficulty of calibrating a model of these processes.

Similarly the decision processes utilised by farmers regarding the choice of crop types and the allocation of land area to each crop type are endogenous to the model. Other factors such as the introduction of new crop types and the capital costs associated with infrastructure (for example boreholes and greenhouses) are excluded from the model.

Because the model includes dynamically interacting processes that operate over a wide range of scales and domains, the model described in this chapter is fundamentally different from standard numerical models, thus fulfilling the first and third research objectives listed in Chapter 2. Further, the fourth research objective (which is an objective that is generally applicable to all well-designed numerical models) has been achieved by the restriction of the model code to the numerical description of the relevant processes.



## **CHAPTER 5: FITTING THE MODEL TO THE HISTORICAL DATA**

The previous chapters have described the historical situation found in the Argolid valley, described the datasets which represent this situation, and defined the processes which will represent the dynamics of the various systems which I have decided are important in the Argolid.

This chapter will apply the model to reproduce the historical, evolutionary pathway that has occurred in the Argolid. The quality of the model will then be analysed to reveal information both about the behaviour of the model and the evolution of the Argolid valley.

A very simple methodology will be applied to fit the model to the historical situation. The datasets described in Chapter 3 will be used as the model domain. Where the data is incomplete or insufficiently well known, values will be selected based upon published data for similar datasets. This process, of running the model with historical data may be basically described as the calibration of the model. If the model has been correctly formulated, and does not omit any important parts of the system, then the model results should be qualitatively and quantitatively close to the actual history.

### **5.1. HYDROGEOLOGICAL HISTORY**

There are two main sources of data for the evolution of hydrogeological conditions in the Argolid. Borehole data presented by Poulovassilis and Giannouloupoulos (1997) includes well tests providing measurements of parameters such as transmissivity of the aquifer. Unfortunately, this dataset is quite small, and is restricted to locations in the central plain of the Argolid. Therefore it can only provide a general outline of the hydrogeological parameters for the model domain.

The second dataset is hydrogeological information derived from an extensive series of interviews with farmers (Allen et al., 1995). The farmers provided information about the number of wells that they had, when they had been bored, the depth of the



boreholes, and the quality and volume of water from each well both when first opened and at the time of the interview. This data was located geographically by the village where the farmer lived. Though this dataset is considerably more qualitative than the first dataset, it has the advantage of a much greater temporal and spatial extent. It provides a broad picture of how conditions in the aquifer have evolved.

These datasets will be used in different ways. The information from the farmers on the evolution of the aquifer is the dataset that will be used to calibrate the model. The borehole data forms the basis of the definition of the hydrogeological domain, which will be varied to make the model match the known historical evolution.

#### *5.1.1. The calibration dataset.*

In order that the model may be considered to be correctly calibrated, there are several datasets that the model should be able to freely reproduce, i.e. the model is only constrained by its internal dynamics and the input parameters and datasets. However there are other datasets that are crucial to the reproduction of the hydrogeological evolution which are exogenous to the model and, *a priori*, must be specified for an accurate calibration. In the first category are the water heads and salinity within the aquifer, whilst in the second category are the climate data and the construction of a major irrigation project.

#### **Water head within the aquifer**

Figures 5.1 to 5.3 show the water pressure head field. The apparent extension of the water head field beyond the boundaries of the model domain is an artefact of the triangulation and interpolation processes used to formulate the field from the data contained in the farmer survey. It should be noted that the aquifer is assumed to be a single layer. The figures show the estimated water heads within the aquifer in the years 1950, 1970 and 1990, respectively. It should also be noted that the aquifer has already begun to suffer from significant over-extraction (and presumably therefore salination) in coastal areas in 1950. This indicates that even before the production of large amounts of irrigated crops, agriculture was having a detrimental effect upon the aquifer.



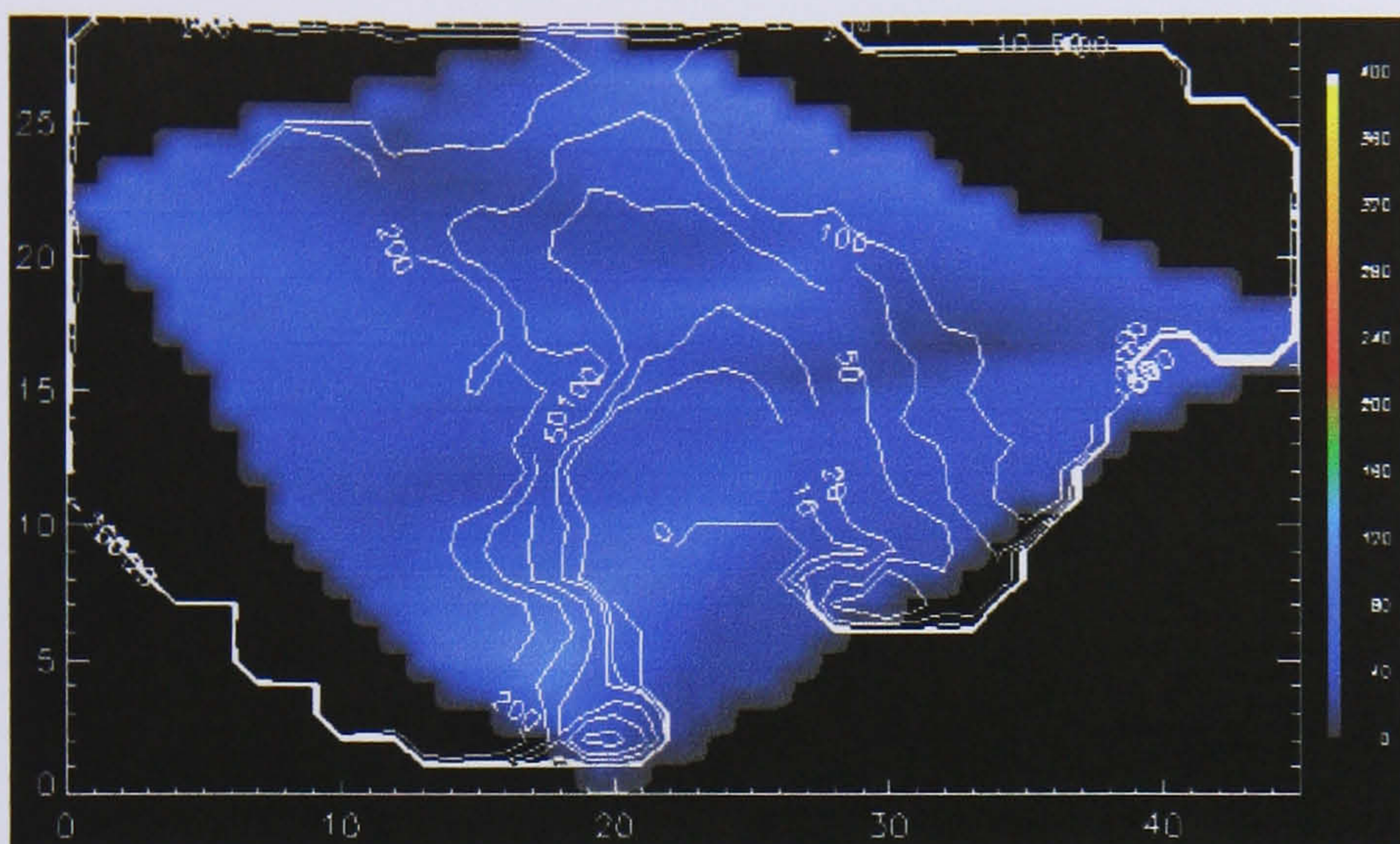
The extremely low water heads found in the periphery of the catchment are probably erroneous and products of the interpolation process, since the locations of the data are clustered in the centre of the valley. Because of the shape of the topography of the valley, it is to be expected that as the height increases, so the water head relative to the surface decreases (becomes more negative). In reality, given the properties of the geology of the periphery, low water heads would be expected.

### **Groundwater salinity**

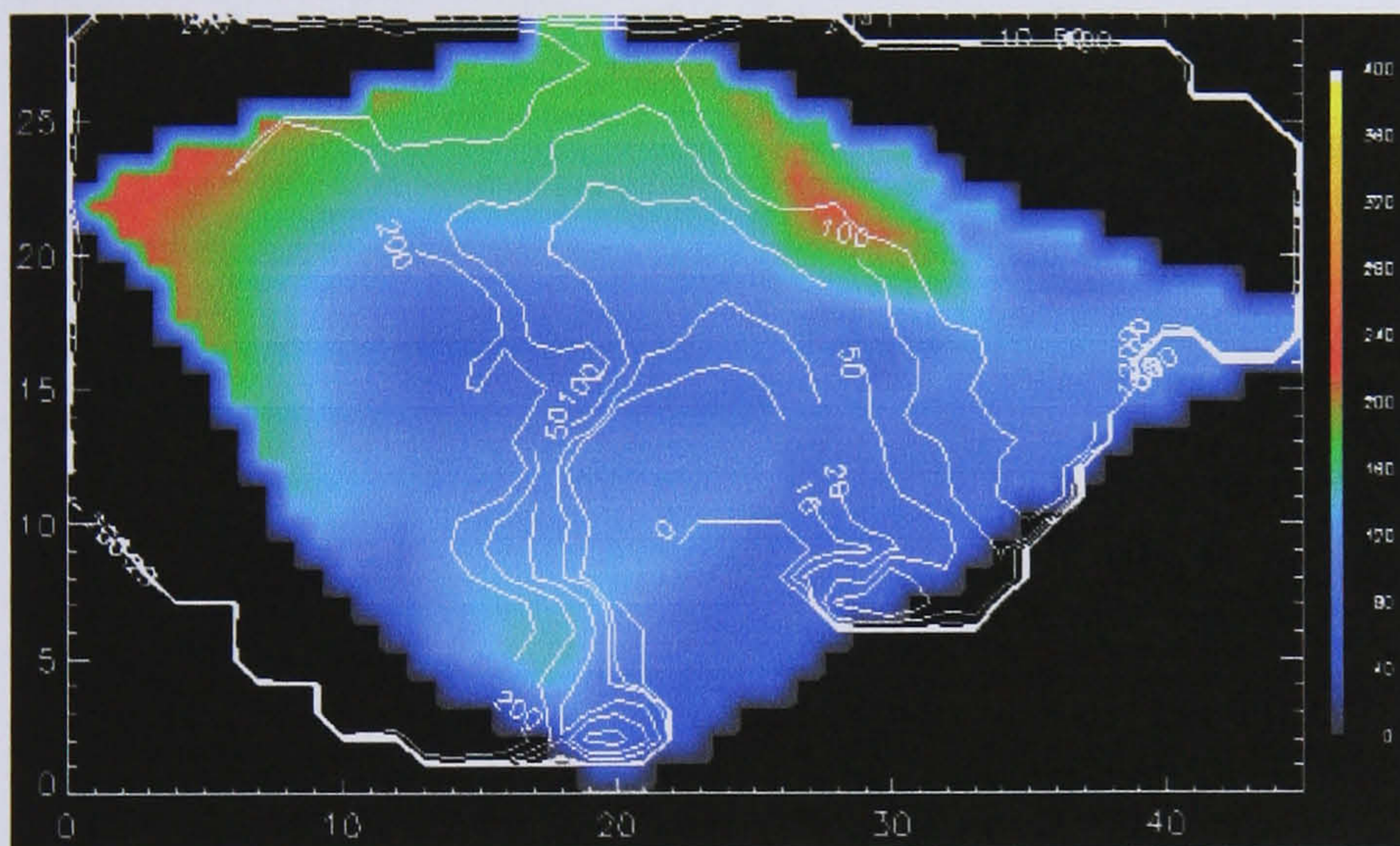
As noted above (Chapter 3) the salinity data suffers from being derived from concentration measurements of a solute, nitrate, which is assumed to be an adequate proxy for seawater. Nitrate was used as a proxy because measurements of nitrate existed due to the adverse implications for potability of high nitrate concentrations. The normal proxy measurement for seawater is chloride, because chlorides are the major solute in seawater (Pond and Pickard, 1983, p.5). The assumption that nitrates are an adequate proxy for seawater is probably invalidated if there is another source for the nitrates found in the aquifer. Unfortunately, agricultural practice in the Argolid is quite intensive, resulting in the large-scale application of chemical additives, and in particular nitrate/phosphate fertilisers. Because of this it is unlikely that the quantitative measurements of nitrates are an accurate reflection of seawater concentrations within the aquifer.

The available data (Poulovassilis et al, 1993) indicates that the averaged measured chloride concentrations in the aquifer reached an approximately constant level at about 400 mg/l in the mid-1980's, though there is considerable inter-annual variation. More recent analysis of groundwater samples (Poulovassilis and Giannolopoulos, 1997) indicate chloride concentrations of up to ~1800 ppm near the coast. If all of this chloride concentration were solely due to seawater ingress, and assuming a chloride concentration of ~ 9000 ppm in sea water, this gives a seawater concentration of 20%. Therefore, though there is insufficient data to calibrate the intrusion of salinity into the model, the general behaviour should be in accord with the above facts.

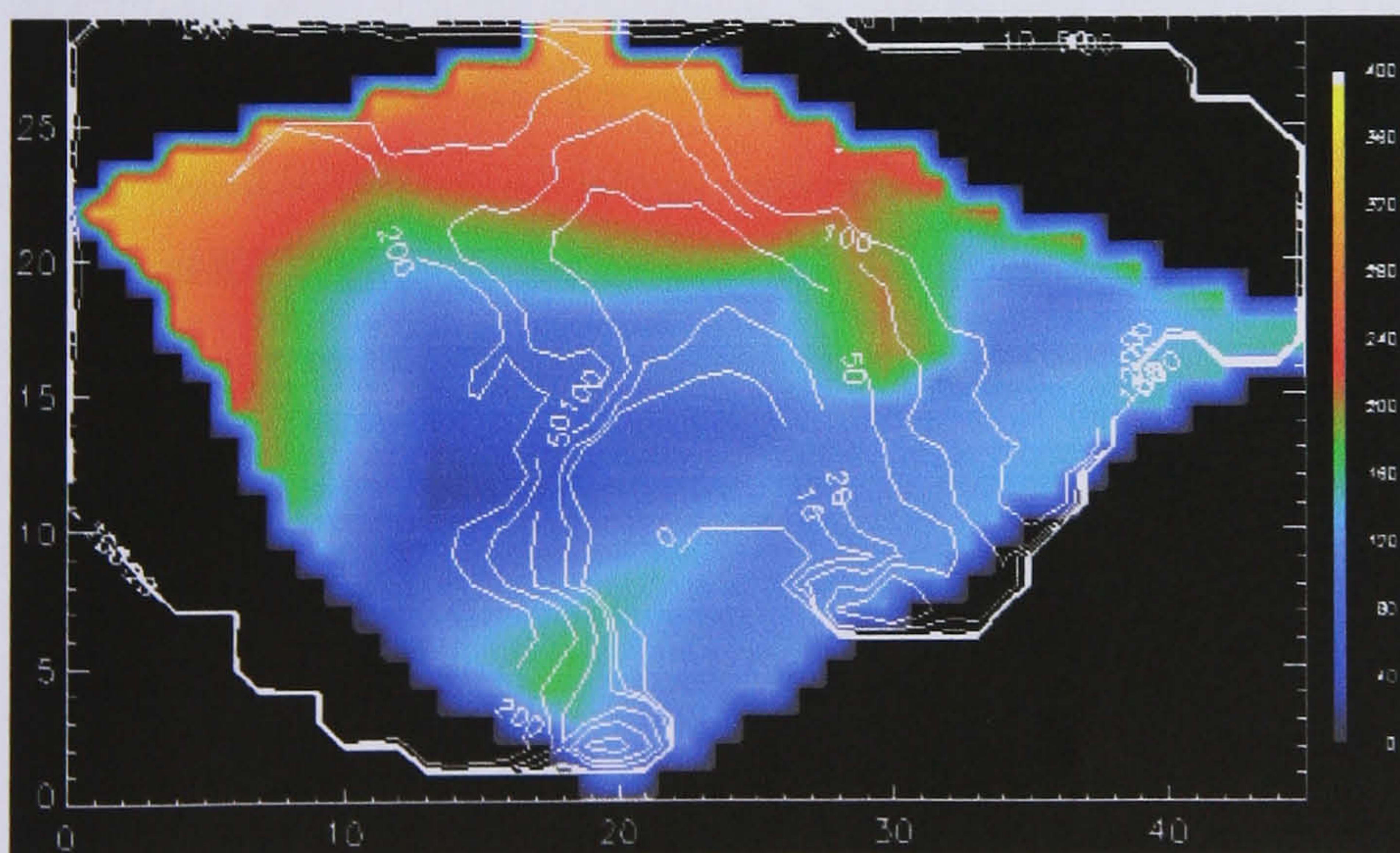




**Figure 5.1** Aquifer water head in 1950. Key indicates depth below surface (m).



**Figure 5.2** Aquifer water head in 1970. Key indicates depth below surface (m).



**Figure 5.3** Aquifer water head in 1990. Key indicates depth below surface (m).



## **The canal**

Of particular importance to the pattern of water resource use in the Argolid is the construction of the canal bringing irrigation water from the springs at Anavolos. The prime motivation for the construction of this canal was to alleviate water shortages and the already incipient problem of groundwater salination.

The canal was constructed in the early to mid-1960's. Figure 5.4 shows the path of the canal. Though the route of the canal was in large part constrained by topographic and engineering considerations, its' precise location and the access of villages to irrigation water from the canal was heavily influenced by local politics (Green and Lemon, 1997). Furthermore the spatial resolution within the model is sufficiently large that the precise location of the canal is not as important as access to irrigation water from it. Therefore, access to irrigation water from the canal is included within the model, rather than having the canal itself explicitly included within the model.

## **Climate**

Of particular importance to the evolution of the Argolid Valley is the climate. As shown in Chapter 3 (Figures 3.4(a) and (b)) the average amount of precipitation in the Argolid has been steadily decreasing, so that present levels are approximately 50% of their pre-war values. This has occurred through a reduction in the amount of precipitation in the "rainy" winter season. Therefore it can be seen that an irrigation project was initially required purely because of the reduction in precipitation and the effect this has on the viability of agriculture in the region.



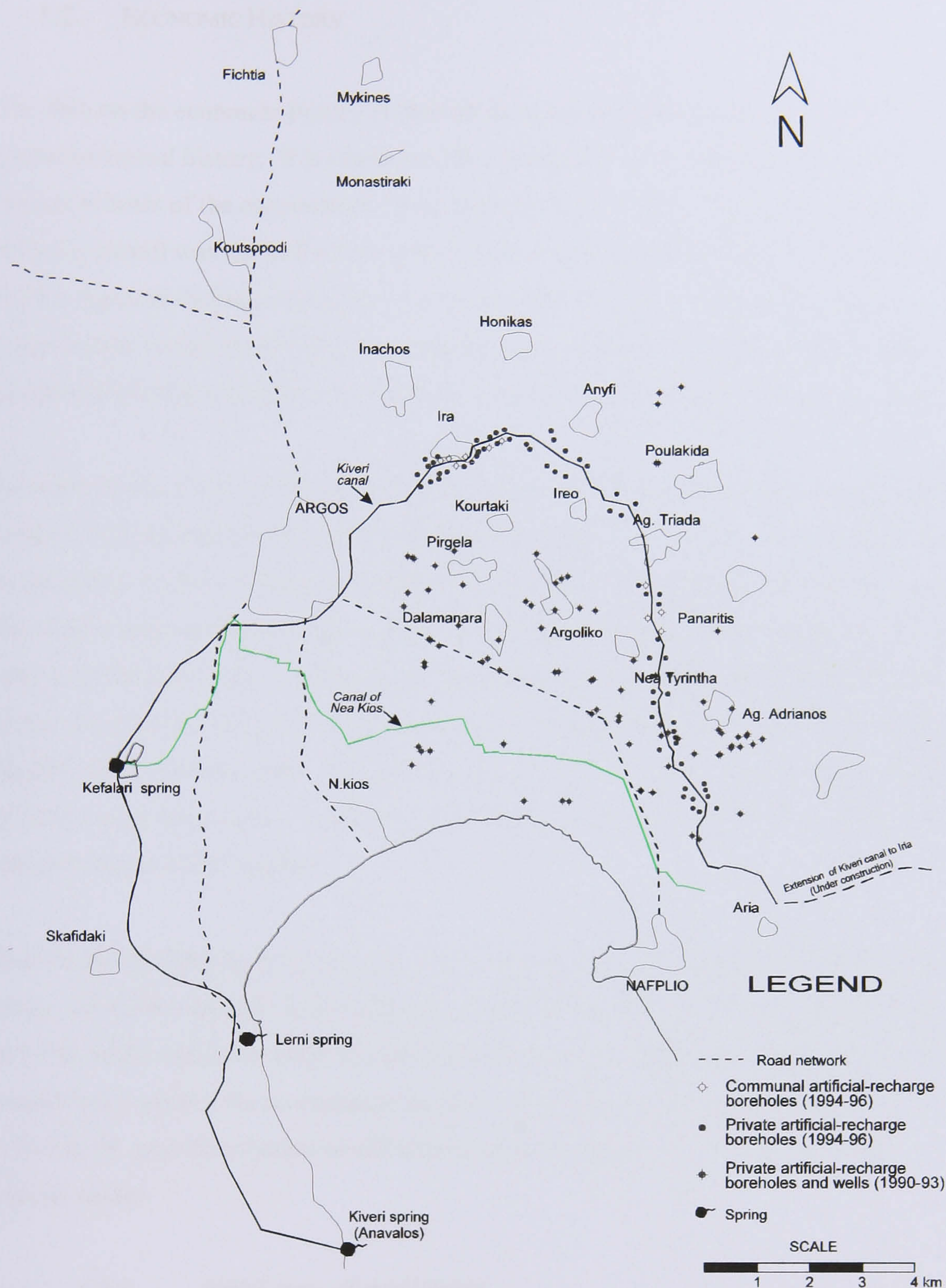


Figure 5.4 Location of canals on Argolid plain (from Poulouvassilis et al, 1994)



## 5.2. ECONOMIC HISTORY.

The data on the economic history is derived from the same farmer survey as the hydrogeological history. It is discussed fully in Allen et al. (1995), and forms the statistical basis of the econometric “crop choice” model. One of the main problems with this model was the lack of any price history. The numerical model in Allen et al. (1995) required forcing (Allen, *pers comm*) in the initial part of each model run to constrain the farmer crop choices to realistic levels, because using fixed prices, made citrus fruit trees an attractive crop to grow, too early in the development of the valley.

Because of this, I use the Bureau of Labor Statistics (1998) partial producer price index (Figure 3.12) to represent the relative changes in prices between two of the crops in the econometric model, namely citrus fruit and vegetables. It is assumed that the price of the other crops, cereals and olives, remains constant. The main advantage of using this data from the perspective of reproducing the historical evolution of the Argolid Valley is that the producer prices of citrus fruit increase steadily with time and with particular rapidity from 1976 onwards. This greatly improves the financial attractiveness of citrus fruit as a crop, and roughly coincides with the general switch to citrus fruit cropping in the central part of the Argolid.

Data on the distribution of crop types in the Argolid is incorporated in the model in two ways. Historical data forms the dataset to initialise the model with the crop distribution in 1950, while data from 1990 will provide a dataset to calibrate the model. However, it should be noted that the econometric model is essentially already calibrated, so any errors in the crop distribution would almost certainly be the result of errors in the aquifer model.

### 5.2.1. *Initial state of agriculture*

The initial distribution of agriculture in the Argolid is derived from the data used in Allen et al. (1995). Figure 5.5 shows the initial distribution of crops by share of



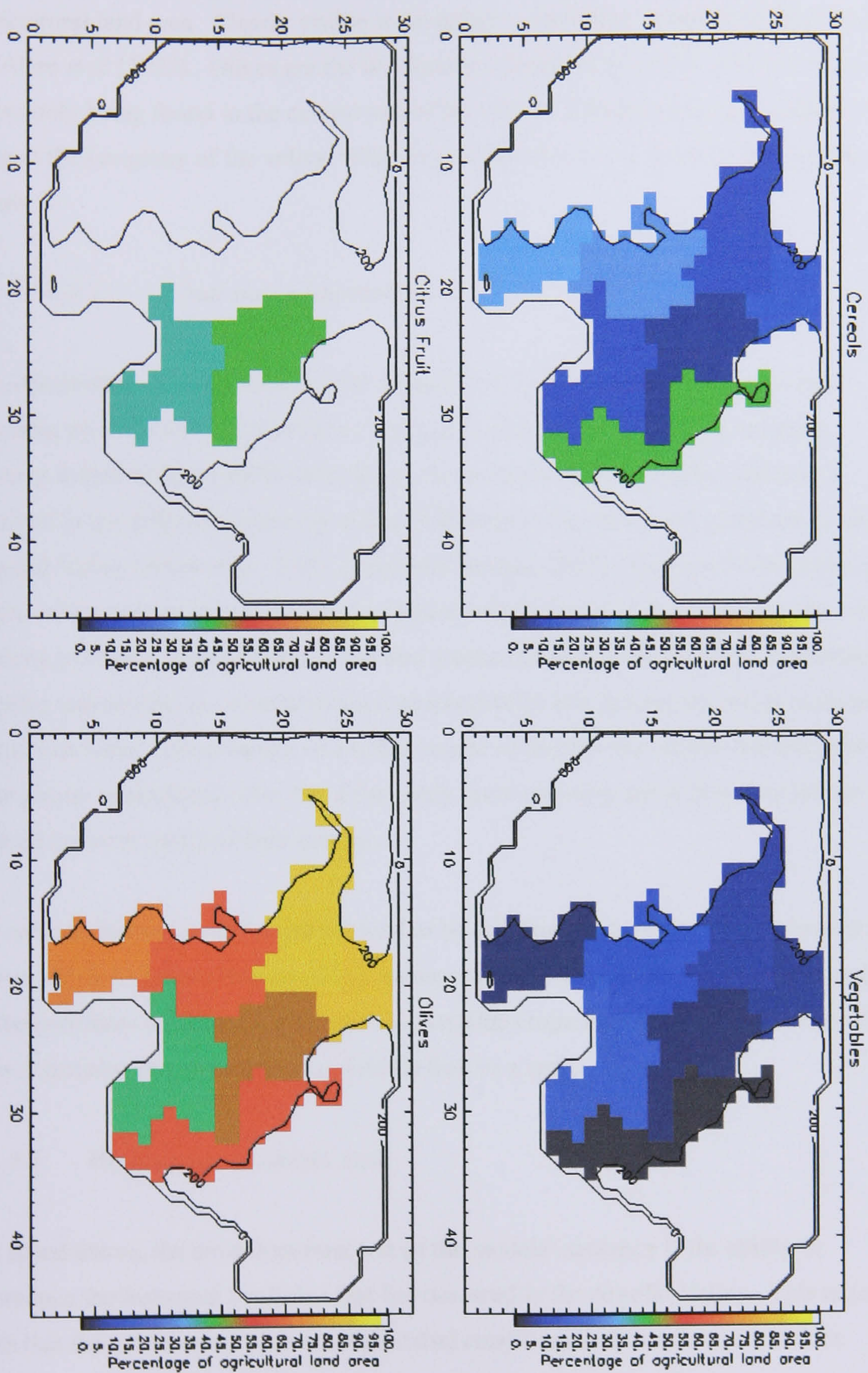


Figure 5.5 Initial distribution of crops by share of agricultural land, in 1950.



agricultural land area. Clearly visible is the pattern of different zones from the analysis by Allen et al (1995). Olives are the dominant crop type in all zones, with Citrus Fruit Trees only being found in the central part of the valley. Cereals are only an important crop in the periphery of the valley, while vegetables have a low share of land area in all zones.

#### 5.2.2. *Final state of agriculture*

The distribution of agriculture in 1991 (Figure 5.6) is characterised by almost monocropping of citrus fruit trees in the central plain, with a more variegated cropping patterns found in the foothills surrounding the central plain. This differentiation is ascribed to the different economic status of farmers in the centre and periphery of the Argolid Valley (Allen et al., 1995; Green and Lemon, 1997). Farmers in the central part of the valley tend to have a second occupation, which provides their main income, with farming providing a supplement. This also means that they have less time to commit to farming and so tend to concentrate on (comparatively) low labour cost crops, such as citrus fruit trees. The presence of another source of income also means that they can take greater agricultural risks, i.e. if they only grow one crop and it fails they still do not lose all (or even most) of their income.

By contrast farmers in the periphery tend to be full-time farmers, for whom growing a variety of crops forms a means of risk management. Furthermore, the higher altitudes in the periphery makes frost damage to susceptible crops such as citrus fruit more likely, thus decreasing the attractiveness of citrus fruit as a crop.

### 5.3. HISTORICAL FIT MODEL RUN.

As stated above, the most important test of the models' accuracy is the ability to reproduce the historical evolution that has occurred in the Argolid Valley. This requires both that the model starts with accurate initial conditions and that these conditions evolve in a "realistic" way.



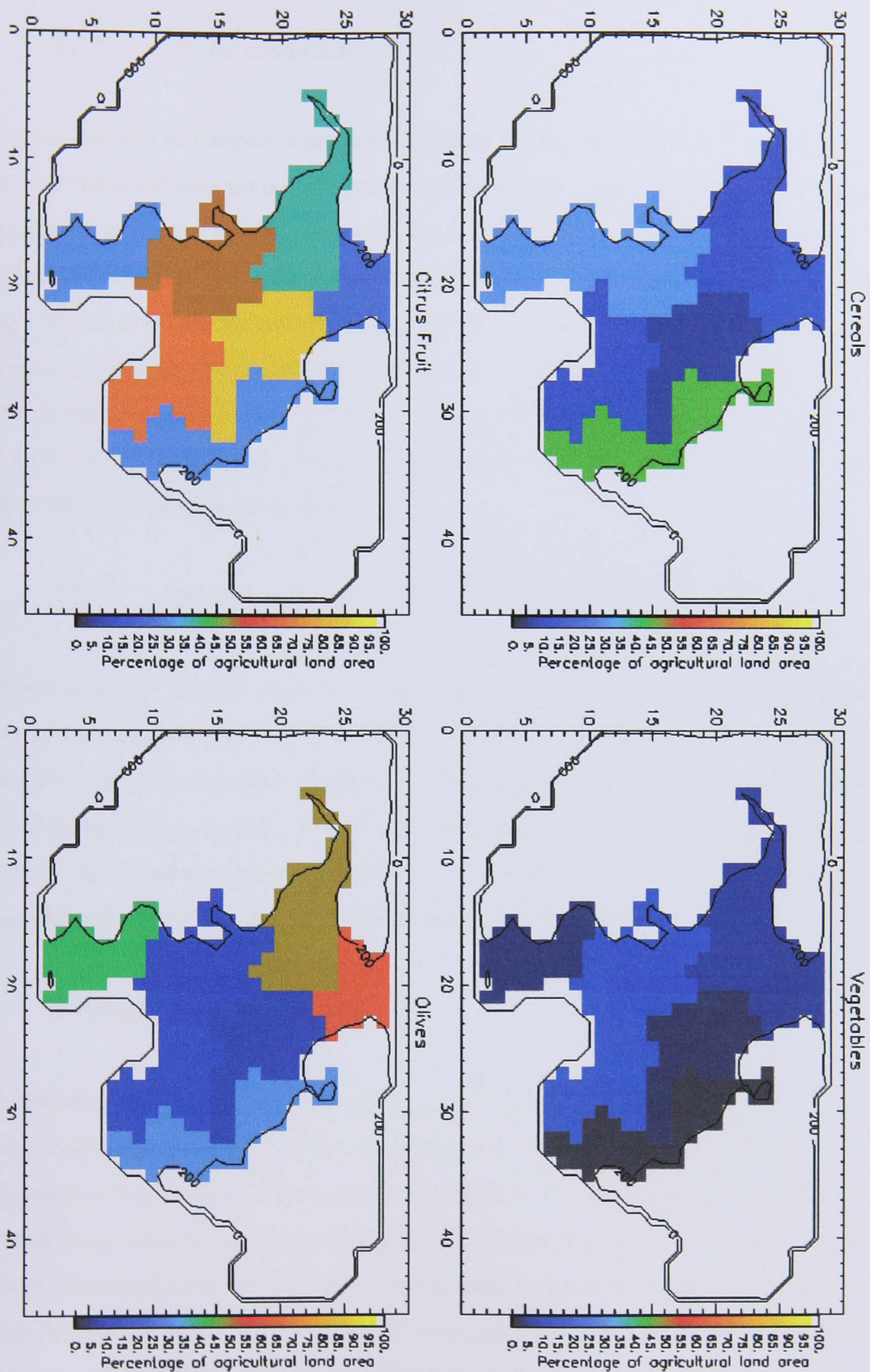


Figure 5.6 Distribution of crops by share of agricultural land in 1990.



### 5.3.1. *Initial conditions*

The data outlined in Chapter 3 provides the basis for the initial state of the model. However these datasets do not always have the necessary spatial resolution that is required for use in the model. This is particularly true for the water table and crop distribution datasets, where the data is classified by village. Interpolation of these data onto a spatial grid (see for example Figures 5.1 to 5.3) does not provide the necessary resolution of features for the model, because the horizontal scale (i.e. approximate distance between villages) is significantly greater than the grid size in the model. Therefore, it is expected that the model output will show significant localised differences from the historical data.

### 5.3.2. *Model parameters for the historical simulation*

The values for the various model parameters have been discussed extensively above, however certain parameters are particularly uncertain. The values of these parameters essentially form the degrees of freedom in which the best fit of the model to the data may be searched for. In order to reproduce the historical conditions, these parameters should be given values which are believed to be close to their true values, assuming that the model reproduces the dynamics of the water resource system.

### **Hydrogeological parameters**

The primary hydrogeological parameters are the vertical and horizontal hydraulic conductivity (ease of flow of water through the aquifer) and the storativity (the proportion of water within a unit volume of aquifer). For the central plain there exist some well test measurements (Poulovassilis and Giannolopoulos, 1997), which provide a direct measurement of the hydraulic conductivity and storativity in individual layers within the aquifer. However, because of the complexity of the structure of interleaved layers of sand (aquifer) and clay (aquiclude) the individual measurements must be converted into generic parameters for the different geological classifications used within



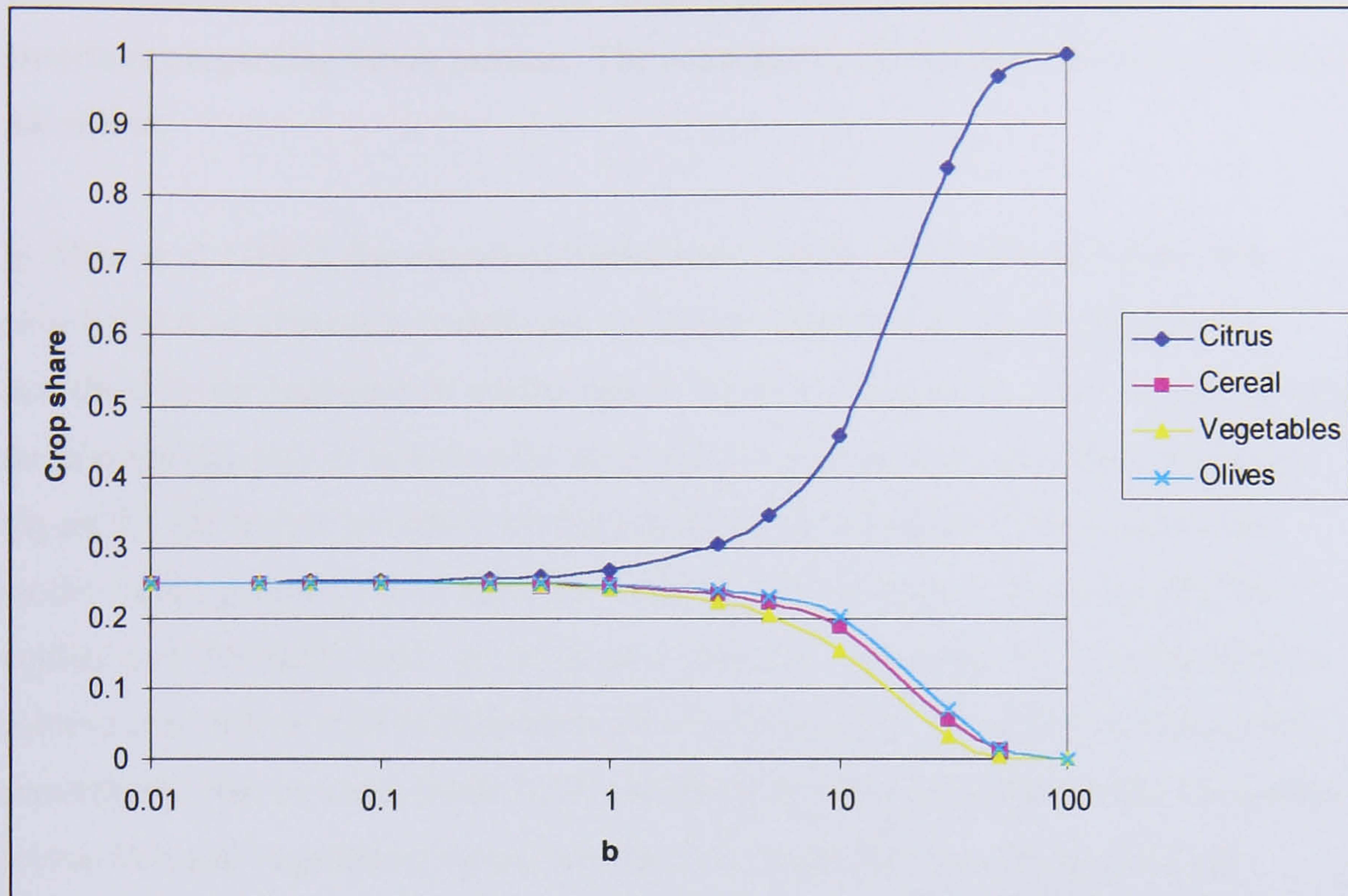
Model code	Geological description	Vertical hydraulic conductivity	Horizontal hydraulic conductivity	Storativity (%)
1	Coarse alluvial	$2.5 \cdot 10^0$	$10^1$	25
2	Fine alluvial	$5 \cdot 10^{-3}$	$10^{-1}$	2.5
3	Medium alluvial	$5 \cdot 10^{-3}$	$10^0$	14
4	Igneous	$10^{-2}$	$10^1$	1
5	Sandstone	$10^{-4}$	$10^{-3}$	10
6	Flysch	$10^{-6}$	$10^{-5}$	12
7	Dolomite	$10^{-6}$	$10^{-5}$	10
8	Karstic limestone	$10^{-2}$	$10^1$	15

**Table 5.1 Hydrogeological parameters used for historical simulation.**

the model (fine, medium and coarse alluvial deposits). This derivation of *effective bulk properties* is standard hydrogeological practice when modelling rock bodies that contain large inhomogeneities on a scale below that of the model (Anderson and Woessner, 1992, p.329). Moreover, there are no *in situ* measurements for the karstic hills surrounding the valley, which in fact compose the majority of the catchment area. For these regions, the hydrogeological parameters must be taken from the published values of properties of similar types of geological material from other locations (Domenico and Schwartz, 1998, p.39; Ford and Williams, 1989, p.131 and 137).

Table 5.1 lists the eight different geological classes and gives the values of the parameters used in the historical simulation. The values used for types 1,2 and 3 are derived from Domenico and Schwartz (1998), together with the results of the well test measurements (Poulovassilis and Giannolopoulos, 1997). The storativities assigned to type 1 and 2 are approximately one quarter of the typical value for these types of material, to take account of the presence of the clay layers in the aquifer (cf. Figure 3.2). Types 4,5 and 6 are taken solely from Domenico and Schwartz (1998), while types 7 and 8 are taken from Ford and Williams (1989). The values chosen are generally at the upper end of the quoted ranges for hydraulic conductivity, to account for the presence of





**Figure 5.7 Idealised variation in crop share with empirical coefficient  $b$ .**

channels and underground rivers which penetrate through, and are a characteristic of, the karstic terrain.

### **Econometric parameters.**

The econometric parameters that are particularly unknown or arbitrary are the crop prices, and the rationality of the farmers. In Chapter 3, a dataset giving producer price history for two of the crop types (citrus fruit and vegetables) was introduced (Bureau of Labor Statistics, 1997, hereafter referred to as BLS) but there is no long-term price history for cereals or olives. The crop price is further complicated by government subsidies and in recent years by the Common Agricultural Policy of the European Union. The effect of these subsidies is to guarantee the farmers a higher price for their produce than the BLS dataset (assuming that the BLS data is an accurate corollary for world prices). Furthermore, these subsidies are known in advance and recalculated periodically (Ritson and Harvey, 1997, p. 4) and so may be expected to have a



disproportionate effect on the farmers' behaviour because of the reduction in uncertainty regarding future income. The econometric model does not take account of this effect.

In Allen et al. (1995), the empirical "rationality" coefficient  $b$ , which defines how closely the land allocation to different crop types follows the "ideal" distribution described by the econometric model, had to be set to a low value. This implies that the farmers are not very sensitive to the profitability of crops when allocating land area. Figure 5.7 shows the variations in crop share that the formulae in the econometric model would generate for an idealised location with soil type 5, assuming that the aquifer is at the initial level. It can be seen that quite high values of  $b$  are required to achieve crop shares such as have been seen in the Argolid. Furthermore it should be remembered that as water levels in the aquifer drop, the crops which require irrigation (citrus fruit and vegetables) would become less profitable. For the moment this parameter will be kept at the same value of 0.03 that was used in Allen et al (1995).

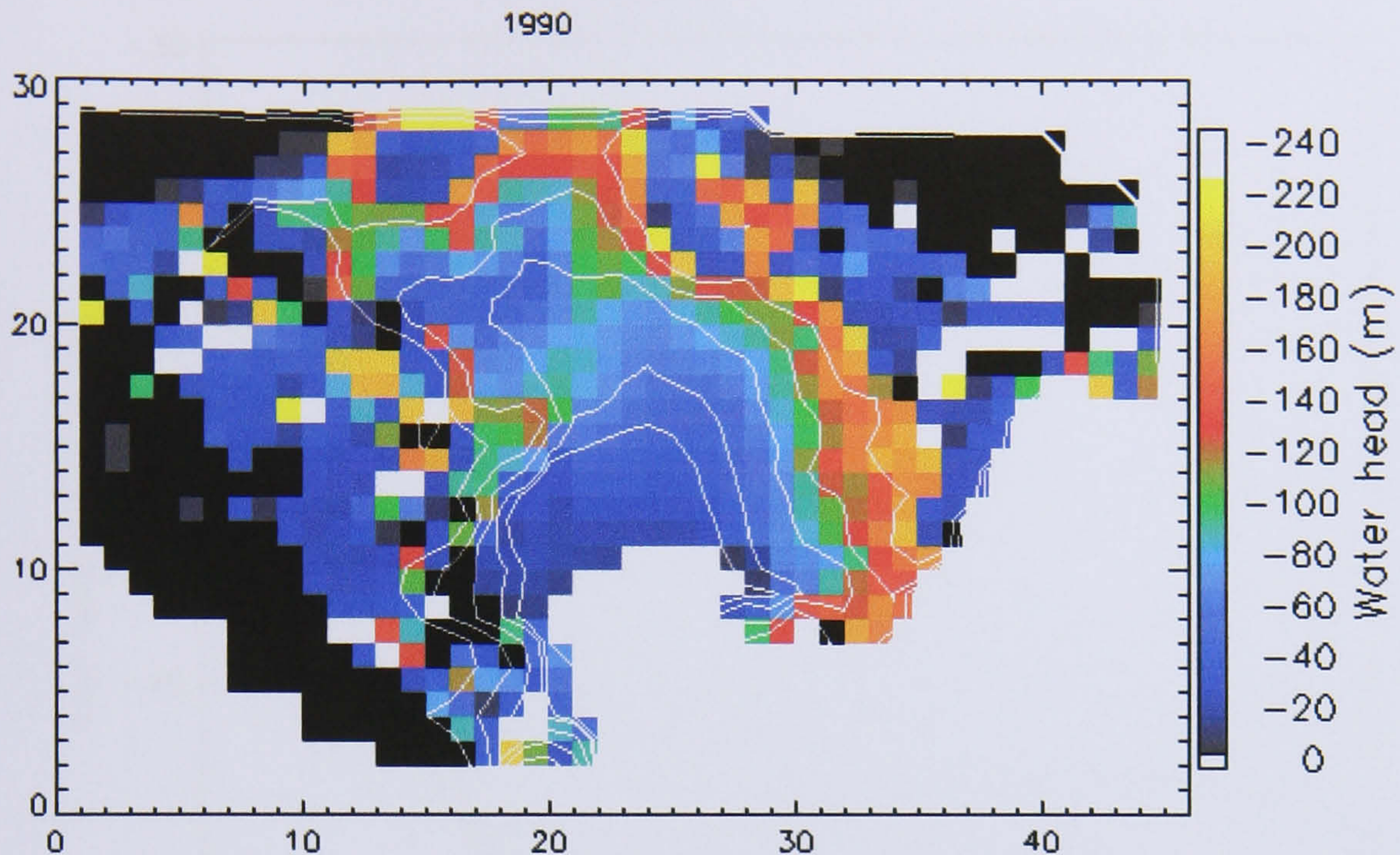
#### 5.4. RESULTS FROM THE HISTORICAL SIMULATION

The model was run for a period of forty model years with the above parameters, using a timestep of 24 hours in the hydrogeological model. The model output was stored at 6 monthly intervals, on day 90 and day 273 (spring and autumn).

##### 5.4.1. *Hydrogeological results*

Figure 5.8 shows the spatial distribution of modelled water head in the aquifer in 1990, while Figure 5.9 shows the change in the mean modelled water head for the central part of the aquifer, defined as being the area with a topographic height of less than 100m, over the length of the model run. It can be seen that the modelled distribution in Figure 5.8 agrees well with Figure 5.3, with the exception of the periphery of the model domain. However, as discussed above (cf. Section 5.1.1), distribution in Figure 5.8 fits in with expectations of the distribution of water head, so that the difference between the figures is probably an artefact of the interpolation process used to generate Figure 5.3.





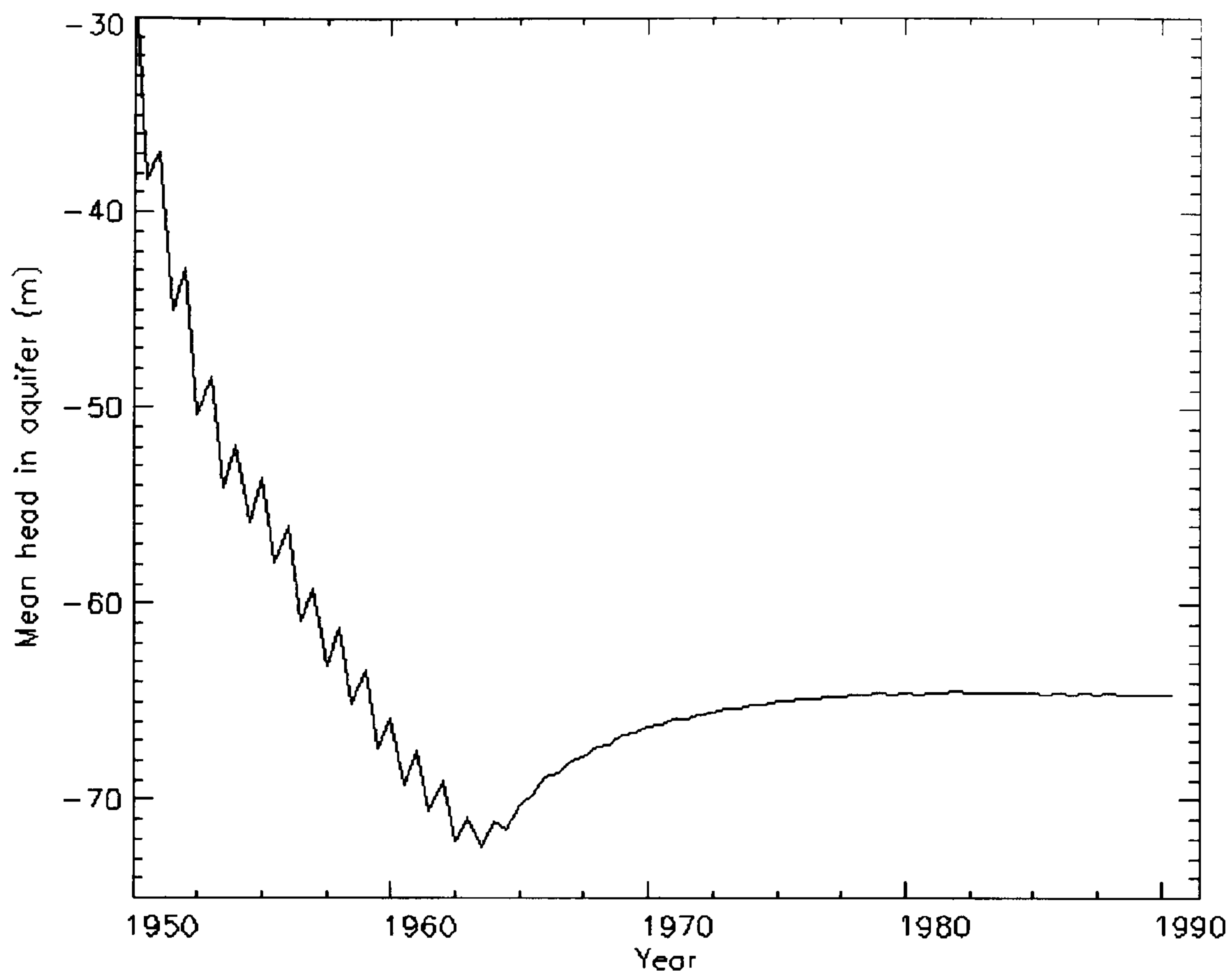
**Figure 5.8 Modelled hydraulic heads in 1990.**

Figure 5.9 shows a far more rapid decrease in water levels within the aquifer than expected. A short time series of measurements (1965 to 1967 and 1985 to 1992) of the aquifer hydraulic head, indicates a mean head of  $-30$  to  $-65$  m (Poulovassilis et al, 1994) with the minimum in 1990 and higher intra-annual variations than are seen in Figure 5.9. Differences in the magnitude of the intra-annual variation may be due to inaccuracies with the crop shares, resulting in too low extraction of groundwater for irrigation.

Also clearly visible in Figure 5.9 is the effect of the construction of the canal in the early 1960's, reducing the requirement for irrigation water. This both halts the decline in the mean hydraulic head and reduces the intra-annual variability.

The rapid decline in hydraulic head implies three possibilities. The first is that the horizontal hydraulic conductivity is too low, thus the extraction that is taking place is not being sufficiently balanced by inflow from the rest of the aquifer. Though the





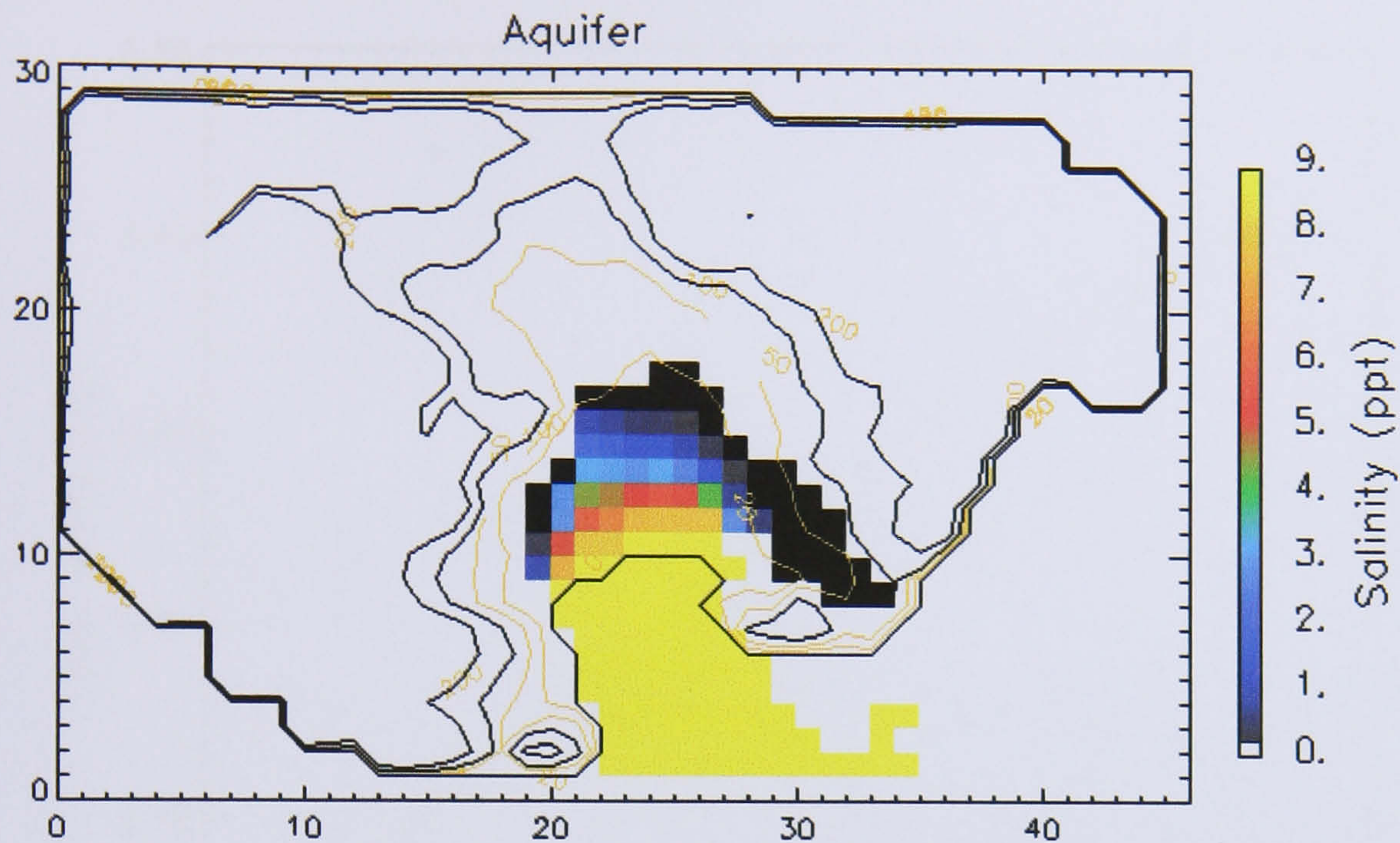
**Figure 5.9 Mean modelled head in central part of the aquifer.**

values of hydraulic conductivity chosen were at the upper end of the quoted ranges, the presence of channels in a material would increase the effective bulk hydraulic conductivity. Thus a higher hydraulic conductivity than the physical properties of the materials suggest may be required.

The second possibility is that the vertical hydraulic conductivity is too low, so that less water is percolating down into the aquifer from the surface. This seems unlikely given that the central part of the valley, to which Figure 5.9 refers, has a clay cap. However, it may be true for the periphery, and in turn affect the model results by reducing the recharge which occurs there, and in turn then flows horizontally into the central valley.

The third possible cause for the rapid decline is that water is being extracted from the



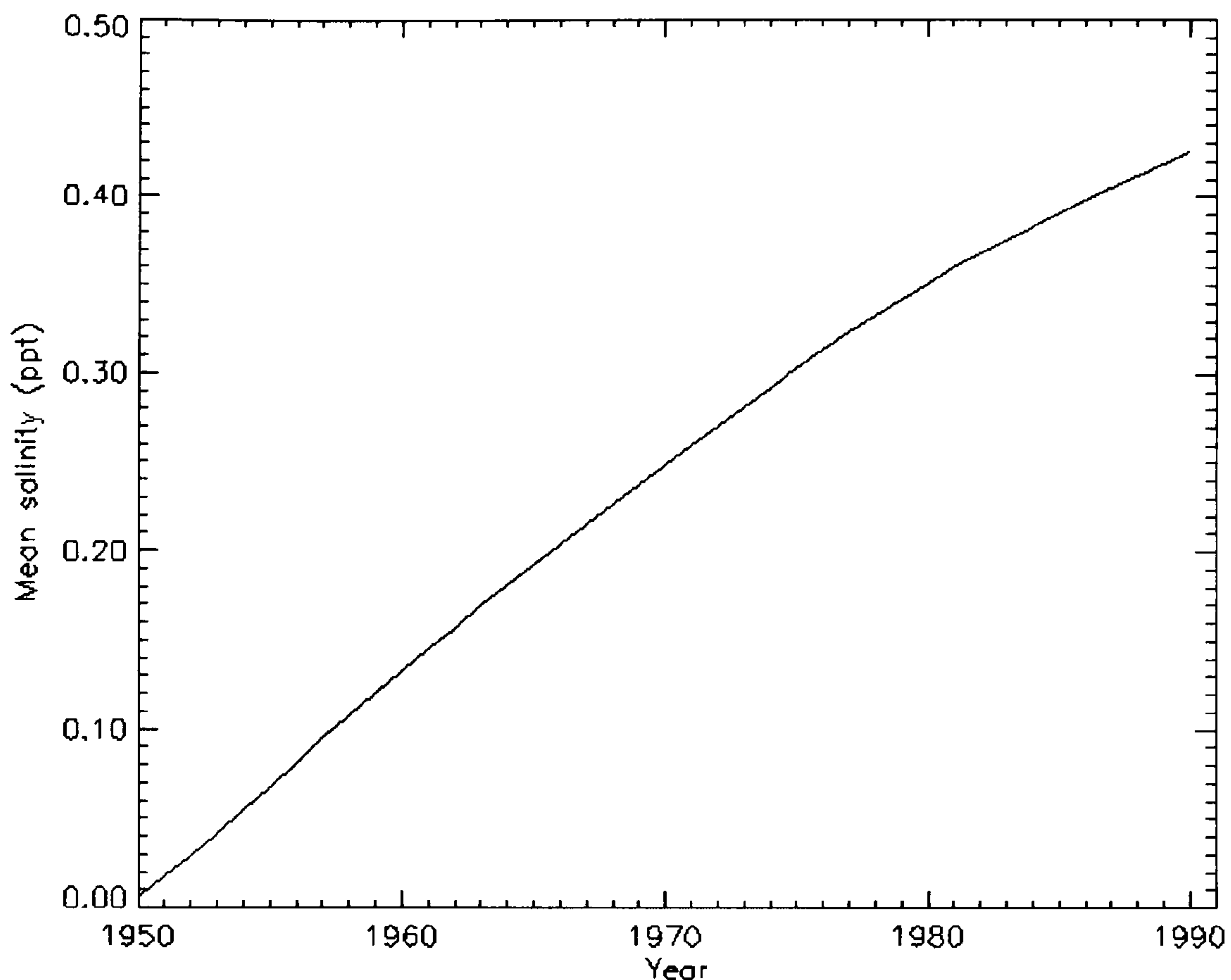


**Figure 5.10 Modelled groundwater salinity in 1990. Key indicates salinity concentrations in parts per thousand.**

ground too quickly. The allowed pumping rate included in the model corresponds to the physical rate that small, modern electro-mechanical pumps can extract (~6 litres/sec). However, because the econometric model does not consider the construction of boreholes, the maximum density of boreholes is implicitly allowed from the start of the model run. In reality, the number of boreholes has increased steadily over time, until the maximum legally permitted density of boreholes has been achieved. Given that the modelled share of citrus crops was only ~30-40% instead of the ~60-80% found in reality, this possibility seems unlikely.

The distribution of salinity is shown in Figure 5.10. It can be seen that the modelled salinity of the aquifer reaches almost pure seawater levels at the coast and extends quite far into the central plain. Though the area affected by seawater ingress agrees remarkably well with the distribution of boreholes from which groundwater samples with high salinity were obtained (Poulovassilis and Giannouloupoulos, 1997), the modelled concentrations are different at any given location. As discussed above, the





**Figure 5.11 Modelled mean salinity of the central aquifer in 1990.**

samples reported by Poulouvalis and Giannouloupoulos (1997) indicate a maximum concentration of less than 2 ppt at the coast, but conversely indicate higher concentrations in the interior. This indicates that processes other than advection are affecting the transport of salt through the aquifer. The high proportion of clay in the aquifer near the coast provides the possibility that salt is reacting with the clay particles, and thus being removed from solution. The presence of channels in the aquifer would allow dispersion to also affect the transport of solutes, and would allow advection to transport solutes much faster than allowed for in the model. The affect of channels would also cause highly inhomogeneous salinity distributions.

Figure 5.11 shows the change in the mean salinity of the aquifer over the model run. Again this agrees remarkably closely with the evolution of mean aquifer salinity reported by Poulouvalis et al (1994), where the salinity increased from ~0.1 ppt in



1965 to ~0.4 ppt in 1992. However, Figure 5.11 does not show the variability reported by Poulouvassilis et al (1994), which is a further indication that processes which are not included in the model are affecting solute transport.

Overall, despite the inaccuracies described above, the model reproduces the general pattern of development of the aquifer.

#### 5.4.2. *Econometric results.*

Figure 5.12 shows the modelled crop shares in 1990. By comparing Figure 5.12 with Figure 5.6, it can be seen that the modelled crop share captures the broad pattern of crop distribution in the Argolid. Olives remain the dominant crop in the periphery, and a significant share of agricultural land is now devoted to citrus crops over most of the valley. However, while the overall pattern may be correct, the share of land devoted to citrus crops does not reach the almost mono-cropping levels found in reality. This may be the result of  $b$ , the empirical “rationality” coefficient, having a too low value, or of incorrect prices and costs for some or all of the crops. The effect on the model of varying  $b$  will be explored further in Chapter 6.

Figure 5.13 shows the profits generated by agriculture, and Figure 5.14 shows the volume of irrigation water used. In both figures the effect of the rapid decline in hydraulic head in the aquifer can be seen. As the head declines, it both increases the costs of irrigation water and reduces the amount that can be extracted. In reality it is unlikely that agriculture in the Argolid has been unprofitable for such a long period of time. This provides further evidence that the decline in hydraulic heads seen in Figure 5.10 is unrealistic.

Furthermore, actual irrigation volumes have remained high at about  $1.5 \times 10^8 \text{ m}^3$  of water annually. While the underestimation of the share of land allocated to Citrus fruit may partially explain the low irrigation volumes, a more likely explanation is again that the hydraulic head is too low, thus reducing the supply of water for irrigation in the model.



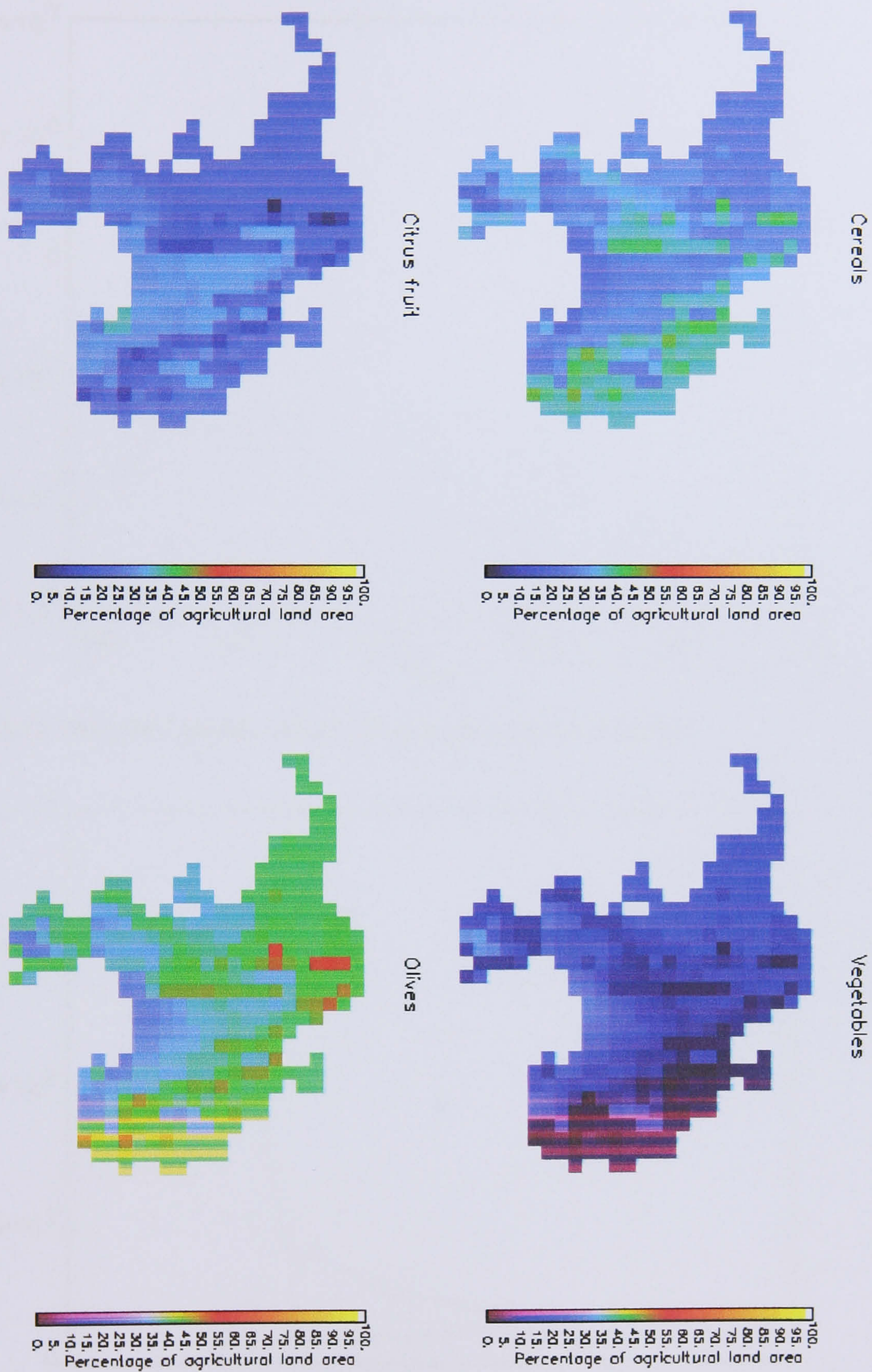
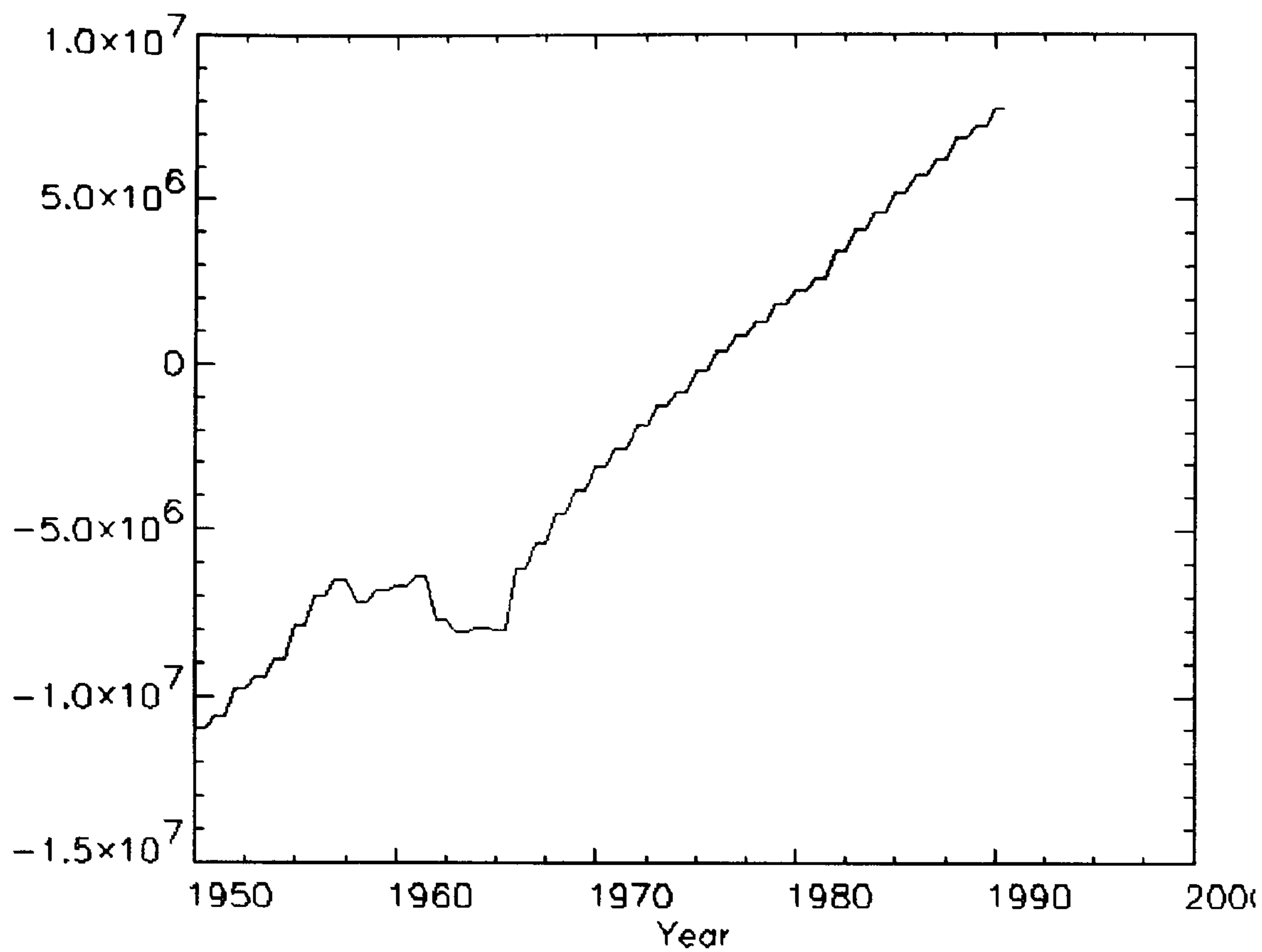
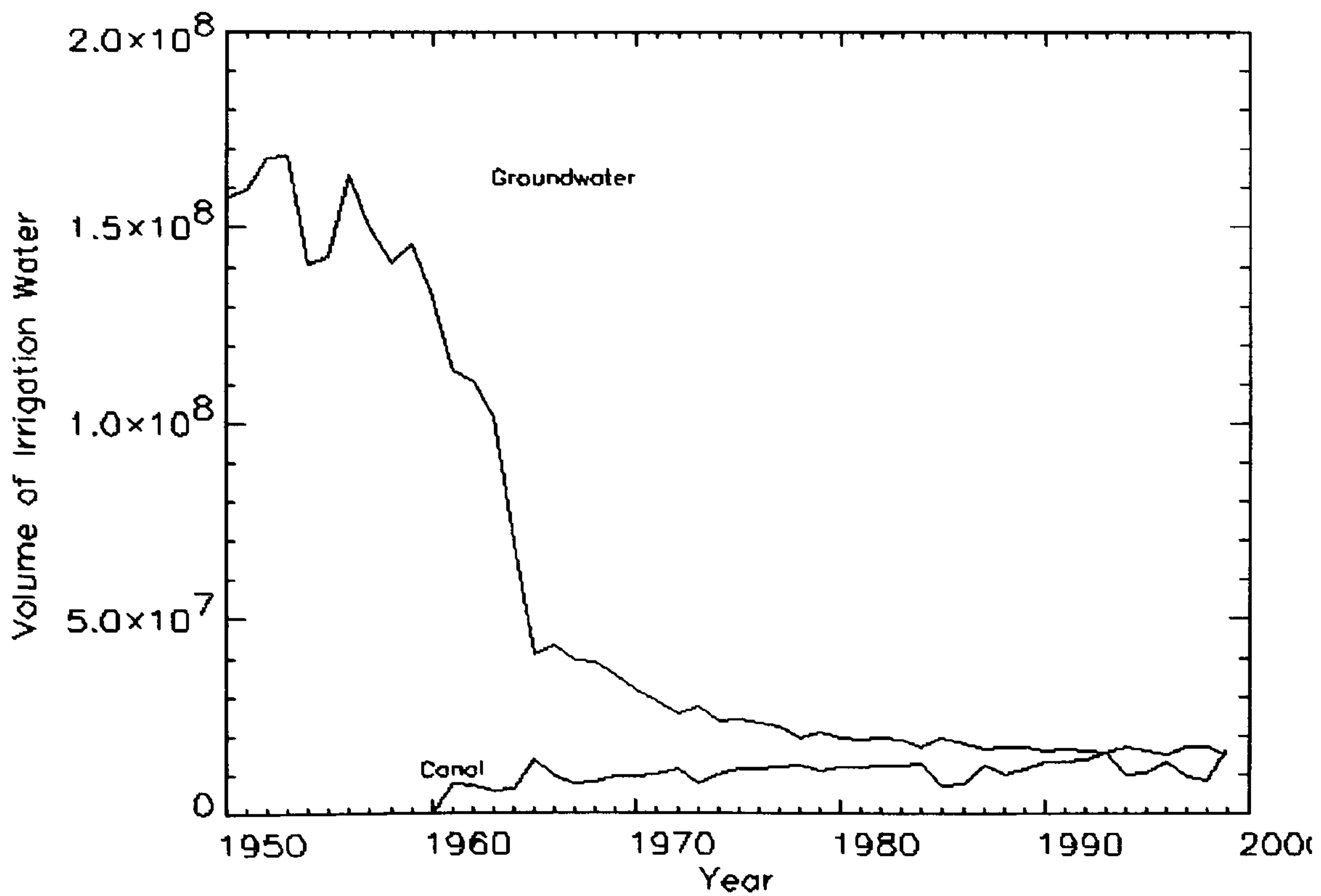


Figure 5.12 Modelled crop shares of agricultural land in 1990.





**Figure 5.13 Modelled profits earned by agriculture in the Argolid.**



**Figure 5.14 Modelled volumes of irrigation water.**



## 5.5. SUMMARY

A model of the water resource system, developed using some simple assumptions about the important processes and parameter values in an area for which there is little quantitative data, reproduces the overall pattern of development of the area reasonably well. Differences between the model results and the available data suggest the presence of inhomogeneity in the physical domain at a smaller scale than is represented in the model.

The ability of the model to reasonably reproduce the dynamics of an area with a comparatively small amount of data and simple assumptions about uncertain parameters indicates that the integrated systems approach to numerical modelling is a valid and useful method for the quantitative study of complex problems in areas where the lack of data would limit the usefulness of a disciplinary approach. This fulfils the second research objective listed at the end of Chapter 2. However, the model does not appear to capture all of the dynamics of the water resource system in the Argolid valley, with failures in both the economic and hydrogeological systems. Thus, at this stage, the model has not achieved the first output objective listed in Chapter 2, of reproducing the historical evolution of the Argolid Valley.

In particular, it appears that failures in the model are mainly due to two factors. In the econometric model, the empirical “rationality” coefficient appears to be too low. This means that agriculture in the model does not approach mono-cropping, but rather remains fairly diverse throughout the model domain.

In the hydrogeological model, the hydraulic head in the central part of the aquifer decreases too quickly. This indicates that either the hydraulic conductivity for the aquifer is too low, or that the storativity should be higher. If the hydraulic conductivity is too low, then recharge of the central aquifer will be too low, resulting in a rapid decline in hydraulic head. If the storativity is too low then the extraction of a given volume of water for irrigation will lower the level of water in the aquifer by too large an amount. This will result in a too rapid lowering of the water level in the aquifer, until



the increased hydraulic head gradients increase the recharge rate and a balance between extraction and recharge is achieved at a lower hydraulic head than happens in reality.



## CHAPTER 6: EXPERIMENTS WITH THE MODEL

Chapter 5 demonstrated that simply by selecting the most obvious parameters for the uncertain parts of the model domain, it was possible for the model to reproduce the dynamics of the water resource system, qualitatively and to a degree quantitatively.

In this chapter, the effect of varying the model parameters on the model fit to the data will be investigated. This will reveal the sensitivities of the model, and should also allow a better fit to the data to be achieved.

### 6.1. INVESTIGATING THE MODELS' SENSITIVITY

The parameters which will be varied are the empirical “rationality” coefficient,  $b$ , in the econometric model, and the hydraulic conductivity and storativity in the hydrogeological model. In the first case, the value of  $b$  used in Chapter 5 was that derived by Allen et al. (1995). However, since this is a purely empirical parameter, and the econometric model has been implemented at a smaller scale, it may be expected that the ideal value for this parameter has changed.

The hydrogeological parameters are uncertain through lack of data. Quoted values of hydraulic conductivity of the same rock type typically vary by four or five orders of magnitude. This high level of uncertainty, combined with the complicated geological structure found in the Argolid allows a large degree of freedom in selecting appropriate values for these parameters.

#### 6.1.1. *Measurement of model fit*

In order to judge the effect of varying these parameters, it is useful to represent the overall model fit with a single value. However, because the water resource system



model includes two radically different systems, two different values will be generated, one for the economic system, and one for the hydrogeological system.

### Economic fit

The quality of the model fit to the economic data will be measured by comparing the share of land allocated to different crops in the different zones of Allen et al. (1995). Mathematically, it is produced as follows:

$$\Delta a = \sum_z \sum_c \sqrt{(A_z^c - a_z^c)^2}$$

where:

$$a_z^c = \frac{\sum_{(i,j) \in z} a_{i,j}^c}{N_{(i,j) \in z}}$$

$a_{i,j}^c$  = share of agricultural land allocated to crop c at location (i,j) in the model;

$A_z^c$  = actual share of agricultural land allocated to crop in zone z (as defined by Allen et al (1995));

$N_{(i,j) \in z}$  = Number of locations (i,j) in zone z;

$\Delta a$  = quality of fit to crop share data.

### Hydrogeological fit

In a similar way to above, the quality of the model fit will be measured by comparing the modelled spatial distribution of hydraulic head with the farmer-derived data, for the central part of the plain. The restriction to the central part of the plain is because it is apparent from Chapter 5 that the farmer-derived data cannot be extrapolated beyond the limits of the central plain when the aquifer is not close to an equilibrium condition. Furthermore, all measurements of hydraulic head in the Argolid have in practice been confined to the central plain. For the purposes of the formulation of this parameter, the



central part of the plain will be defined as that part of the valley with an altitude of less than 100m.

$$\Delta h = \sum_{i,j} \sqrt{(H_{i,j} - h_{i,j})^2}$$

where:

$H_{i,j}$  = historical hydraulic head at location  $i,j$ ;

$h_{i,j}$  = modelled hydraulic head at location  $i,j$ .

For both  $\Delta a$  and  $\Delta h$ , lower values indicate a better fit between the model and the data, with a value of zero indicating a perfect fit. However because of the limitations of the data, extremely low values are not to be expected.

#### 6.1.2. *Rationality coefficient, b*

In Chapter 5, the modelled crop shares did not reach the extreme levels that have occurred in reality, with the central part of the Argolid having ~60-80% of the agricultural land devoted to Citrus Fruit trees. Because of the use of incorrect values either for the prices paid for crops, or for the cost of growing different crops, it is more likely that the cause of the discrepancy is too low a value of the empirical parameter  $b$ . As seen in Figure 5.7, a low value of  $b$  makes it inevitable that the land share allocated to citrus crops will not reach the levels seen in the historical data. Therefore, the model should be run with higher values for this parameter, in order both to see the dependence of the models' performance upon this parameter and to see if a better fit can be obtained.

However, it should be remembered that because the water resource system model is inherently complex, varying  $b$  by such large amounts will not necessarily improve the overall model fit.



### 6.1.3. *Hydraulic conductivity*

One of the possible explanations for the rapid decline in hydraulic head seen in the central part of the modelled aquifer was that the hydraulic conductivity was too low in either, or both, the central part of the aquifer and the periphery. The reason for this conclusion is that because negligible amounts of water percolate directly from the surface into the central part of the aquifer, either in the model or reality. The water in the central part of the aquifer is recharged from the periphery of the valley. Therefore, if the hydraulic conductivity of the central part of the aquifer is too low, recharge waters will propagate too slowly through the aquifer, resulting in a lower recharge rate than actually occurs. Similarly if the hydraulic conductivity of the periphery is too low, then the amount of precipitation entering the aquifer will be reduced, and the amount of this water leaving the periphery and recharging the central part of the aquifer will also be too low.

Given the uncertainty in the values for the hydraulic conductivity, it seems probable that the values used in Chapter 5 are too low. However, in order to understand the sensitivity of the model to this parameter, the model will be tested with both higher and lower values of hydraulic conductivity.

### 6.1.4. *Storativity*

The central part of the aquifer is composed of sand and clay layers. Because the clay layers are essentially impermeable, the effective storativity of the material in this part of the aquifer was reduced to a value approximately one quarter of quoted values (cf. Table 5.1). If this storativity is too low then it would be expected that the effect on the hydraulic head would be to make it change too quickly. In the situation in the Argolid where large scale extraction of groundwater takes place this would result in the hydraulic head dropping more rapidly than it should, until the increased hydraulic gradients increase the rate of water flow into the area and a balance between extraction and recharge is reached. It should be noted that the balance point may lie at a level



where the aquifer has effectively been emptied of water, in which case equilibrium will not be achieved if extraction continues.

## 6.2. RESULTS OF MODEL SENSITIVITY TESTS

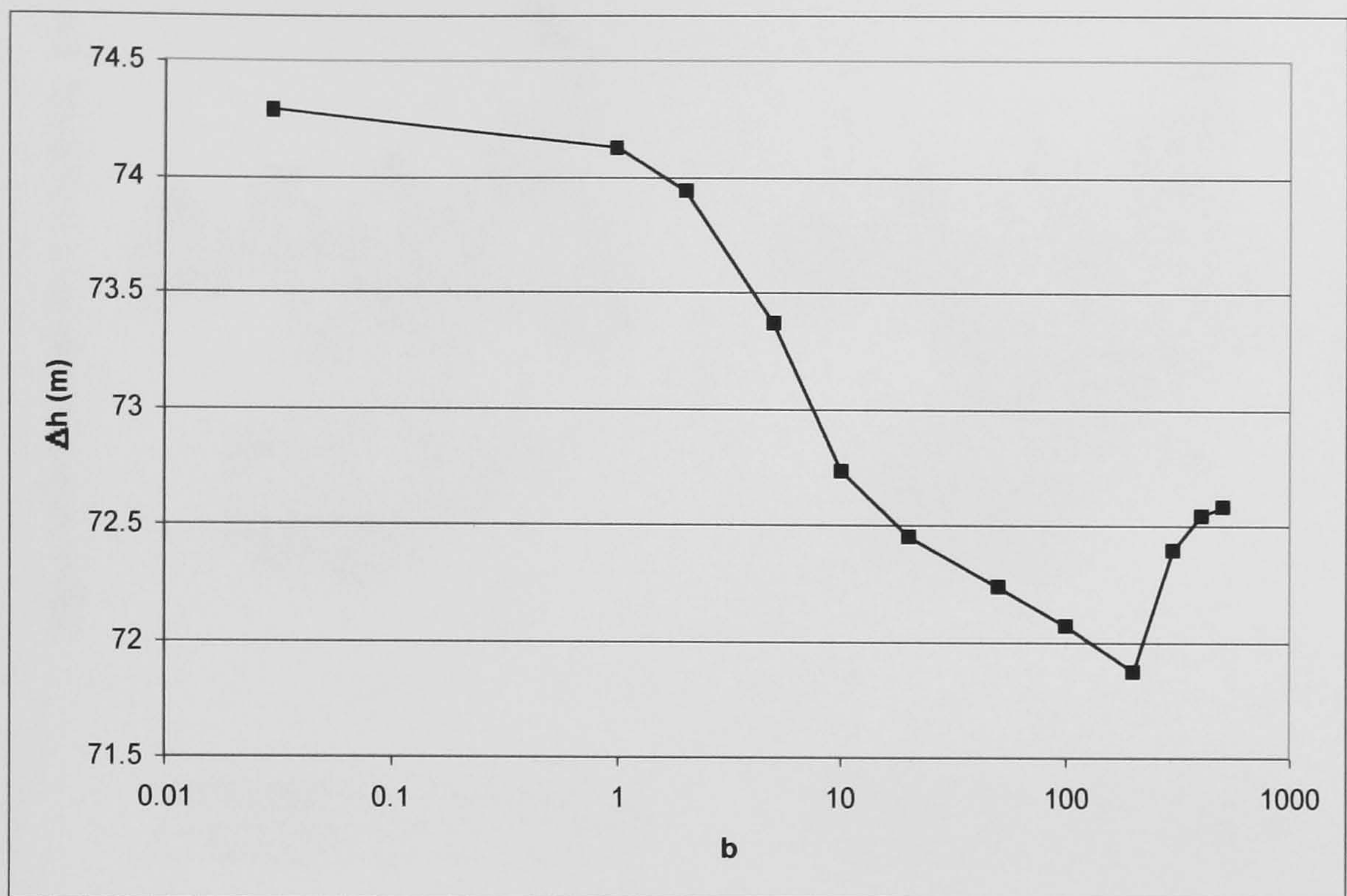
The results of the different series of model runs will be presented in the form of graphs showing how the quality of fit parameters  $\Delta a$  and  $\Delta h$  vary when the value of the various model parameters are changed.

### 6.2.1. *Varying $b$ .*

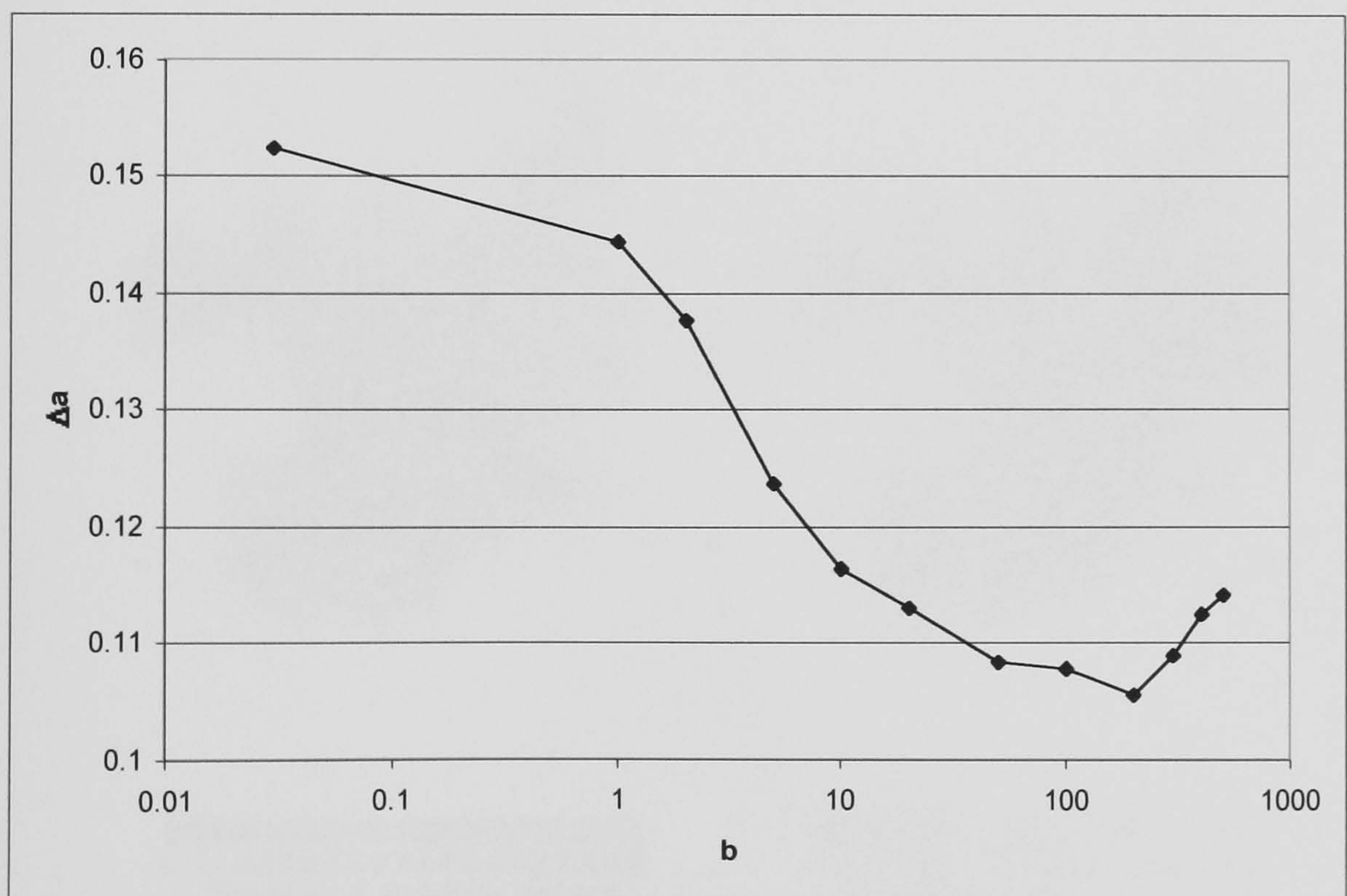
Figures 6.1 and 6.2 show the changes in quality of fit of the model to the known crop share ( $\Delta a$ ) and hydraulic head ( $\Delta h$ ) that result from varying the empirical “rationality” coefficient,  $b$ , between 0.003 and 500. It can be seen that in both cases the best model fit is achieved with the value of  $b$  set at 200. This implies that the farmers in the valley can be assumed to be extremely rational. In Figure 6.3 the modelled distribution of crops in 1990 that results from setting  $b = 200$  can be seen. It is apparent that the reason for the minima in  $\Delta a$  and  $\Delta h$  is that the modelled share of agricultural land allocated to Citrus Fruit does reach the levels found in the Argolid valley. The modelled distribution of land allocated to other crops bears less resemblance to the actual distribution, but it is the crops which require large volumes of irrigation water that are most important for the evolution of the aquifer over time. This explains why the value of  $\Delta h$  follows the same pattern of variation as  $\Delta a$ , because the econometric model is now capturing more of the farmer-behaviour that is important for the aquifer. The similar variation in  $\Delta h$ , also indicates that  $\Delta a$  is a good measure of the overall quality of fit of the model.

Figure 6.4 shows the modelled hydraulic head for the aquifer in 1990, while Figure 6.5 shows the distribution of salinity in the model. Overall, the hydraulic heads and salinity





**Figure 6.1** Variation in quality of fit of modelled hydraulic head  $\Delta h$  with  $b$ .



**Figure 6.2** Variation in the quality of fit of modelled crop share  $\Delta a$  with  $b$ .



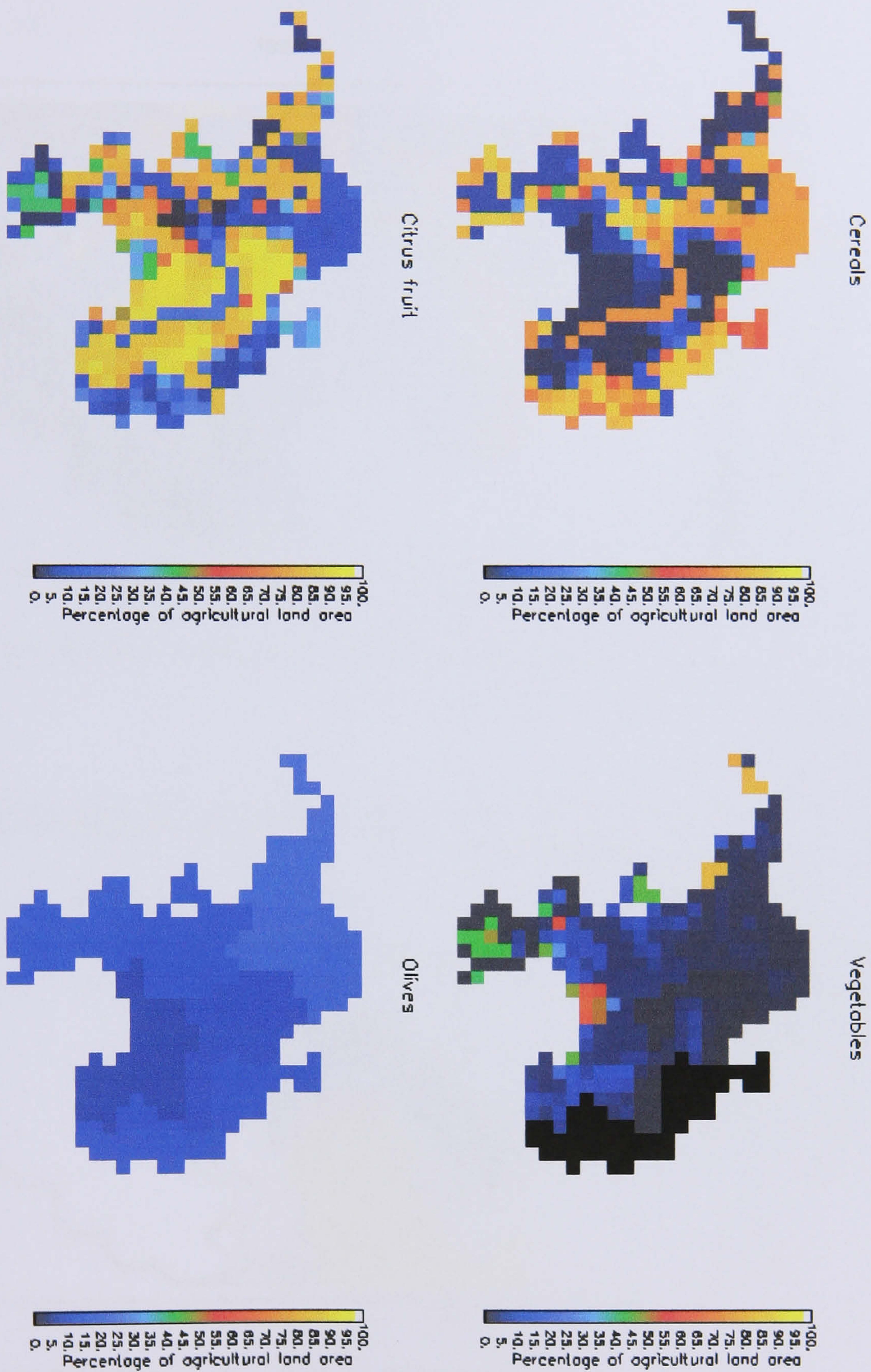


Figure 6.3 Modelled crop shares using  $b=200$ .



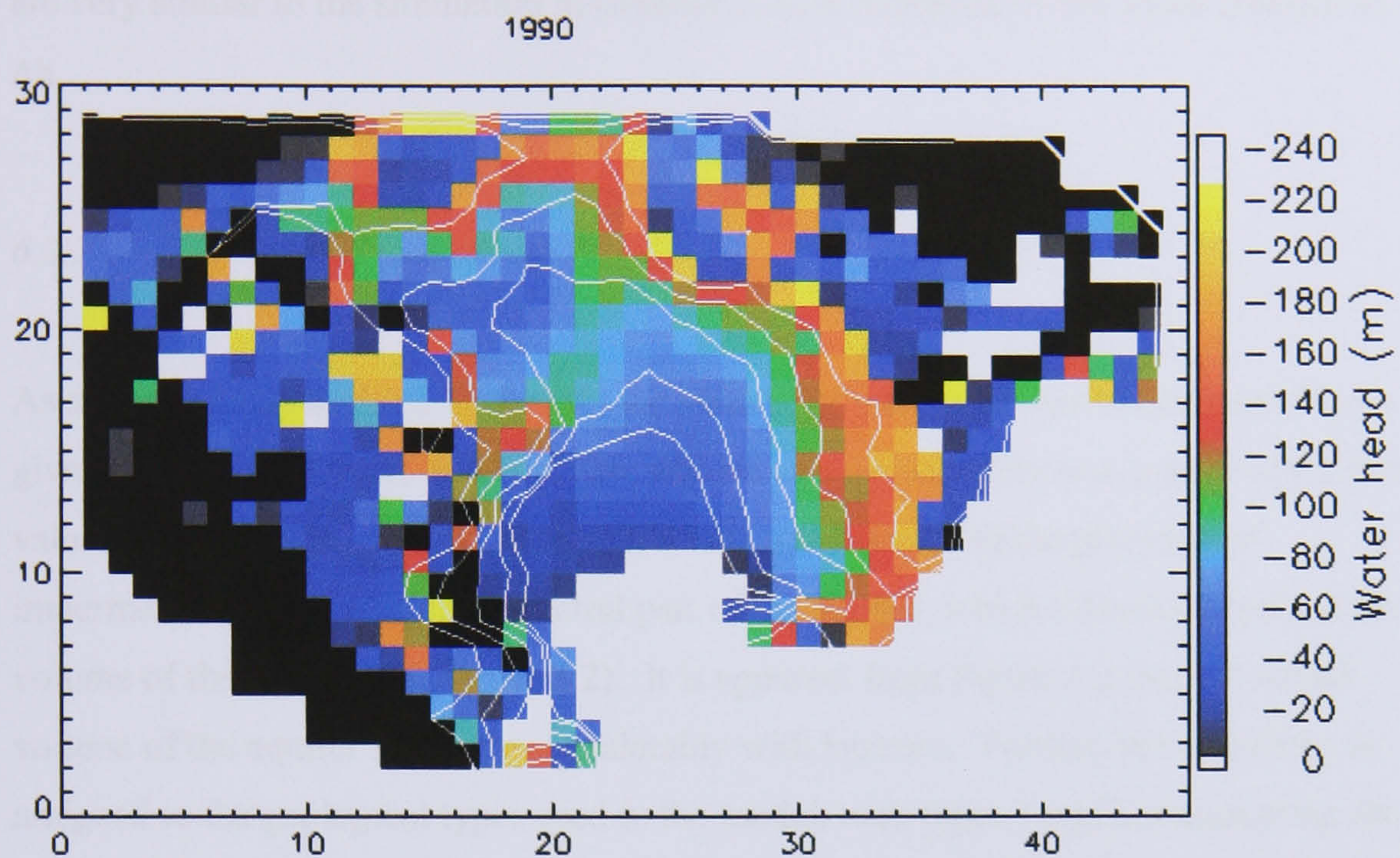


Figure 6.4 Modelled hydraulic heads in 1990, with  $b=200$ .

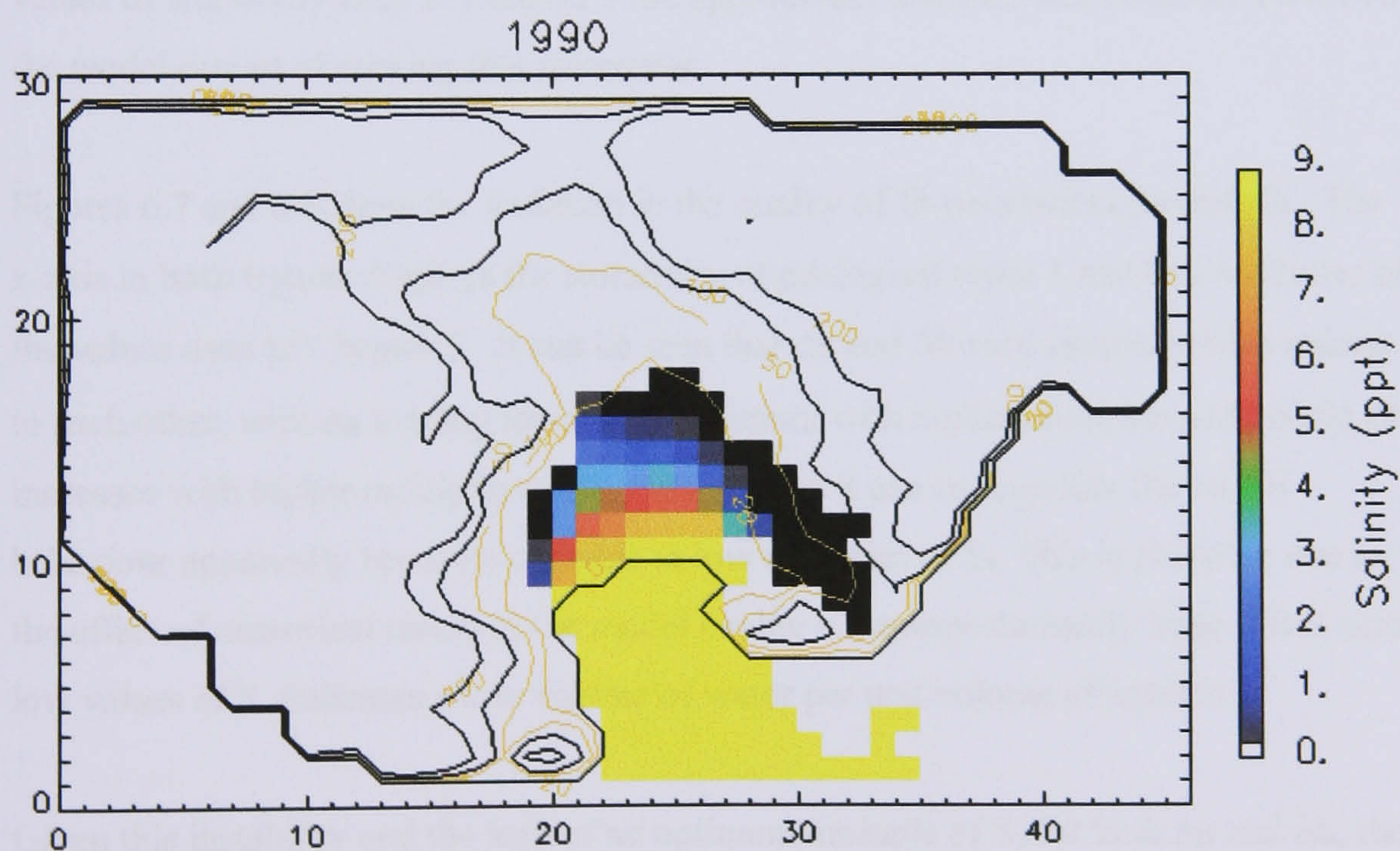


Figure 6.5 Modelled aquifer salinity in 1990, with  $b=200$ .



are very similar to the simulation in Chapter 5, as is indicated by the small changes in  $\Delta h$ .

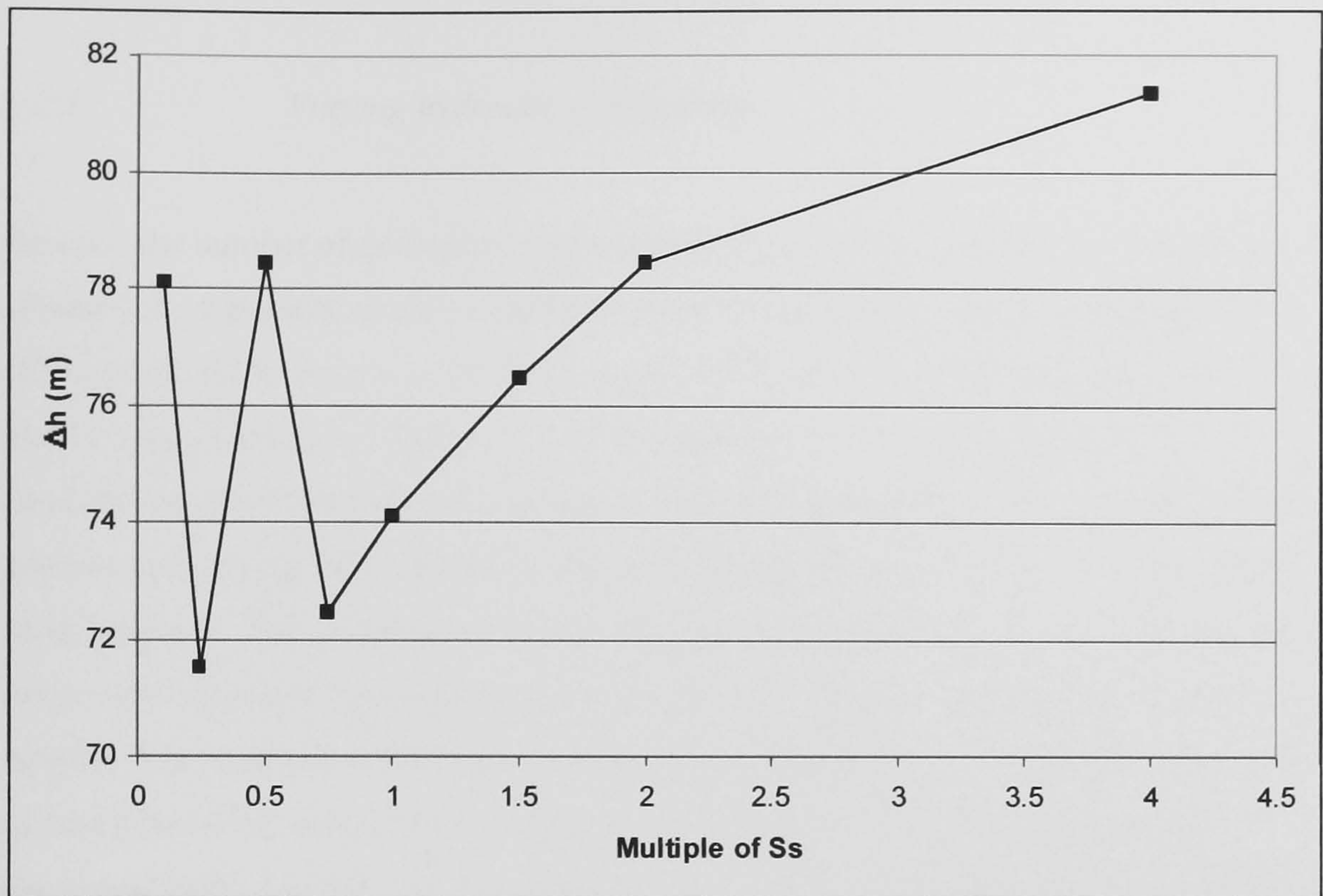
#### 6.2.2. *Varying storativity, $S_s$*

As stated in Chapter 5 (cf. Table 5.1) the volume of water that can be extracted from a given volume of aquifer, or storativity, was set to approximately one quarter of quoted values for the central part of the aquifer. This was because of the presence of impermeable clay layers in the central part of the aquifer, which effectively reduce the volume of the aquifer (cf. Figure 3.2). It is apparent from Figure 3.2 that the actual volume of the aquifer will vary considerably with location. Further, the storativity is assigned to the geological types used in the model, with types 1 and 2 representing the central part of the aquifer. Since these types are amalgams of different geological sequences, it is possible that in some places in the model domain the reduced storativity is inappropriate. Therefore, with these experiments it is hoped to ascertain whether the values of storativity used in Chapter 5 are appropriate, and also determine the effect on the model output of varying this parameter.

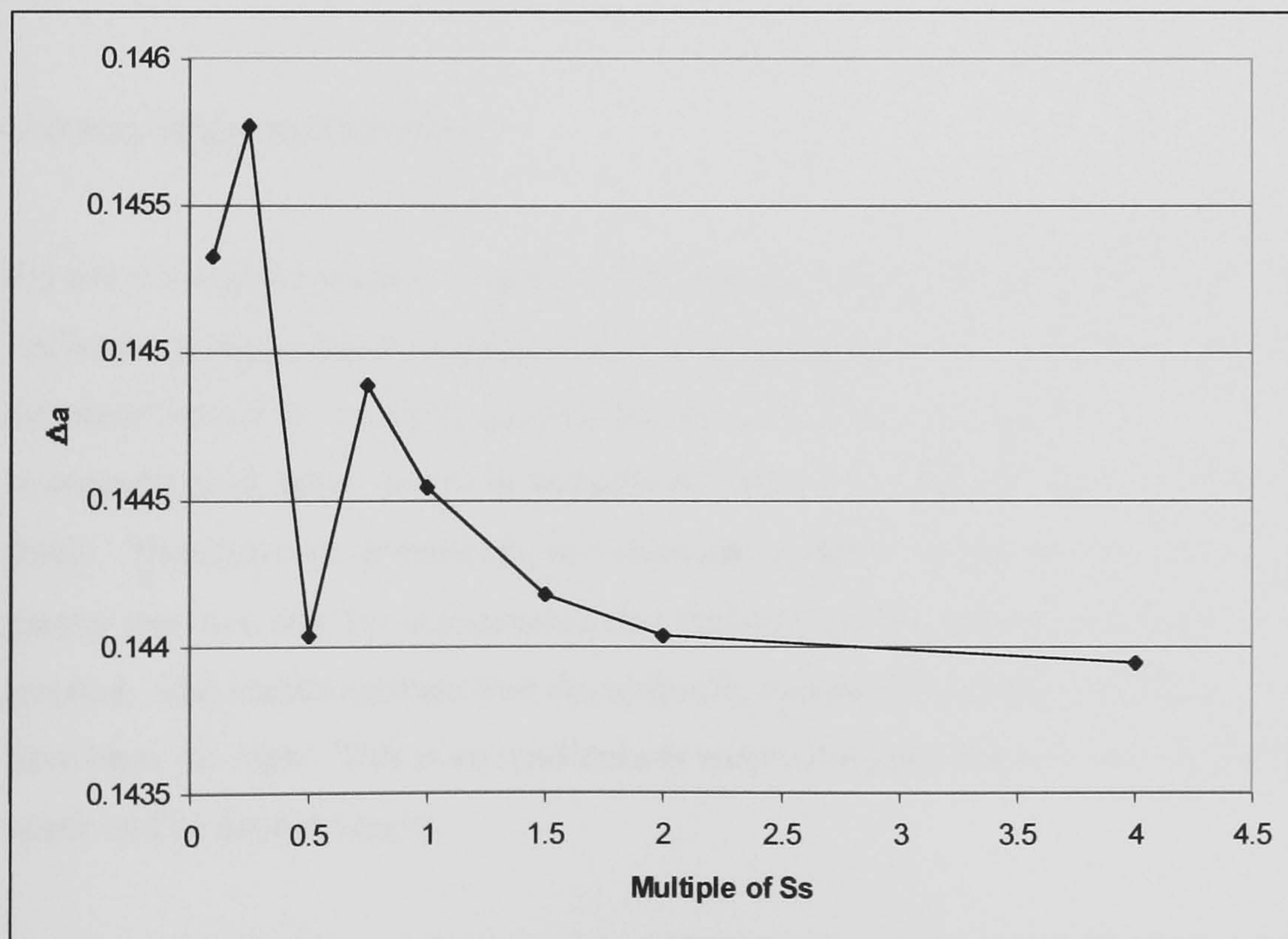
Figures 6.7 and 6.8 show the variation in the quality of fit parameters  $\Delta a$  and  $\Delta h$ . The x-axis in both figures displays the storativity of geological types 1 and 2 as multiples of the values used in Chapter 5. It can be seen that  $\Delta a$  and  $\Delta h$  vary inversely with respect to each other, with  $\Delta a$  tending towards a minimum with higher multiples of  $S_s$  while  $\Delta h$  increases with higher multiples of  $S_s$ . Furthermore it can be seen that the model behaviour apparently becomes unstable at low multiples of  $S_s$ . This is probably due to the effect of numerical errors in the model having a disproportionately large effect since low values of  $S_s$  indicates a low volume of water per unit volume of aquifer.

Given this instability and the lack of an optimum multiple of  $S_s$  for both  $\Delta a$  and  $\Delta h$ , the values of storativity chosen in Chapter 5 appear to be the most appropriate.





**Figure 6.6** Variation in  $\Delta h$  with storativity of geological types 1 and 2.



**Figure 6.7** Variation in  $\Delta a$  with storativity of geological types 1 and 2.



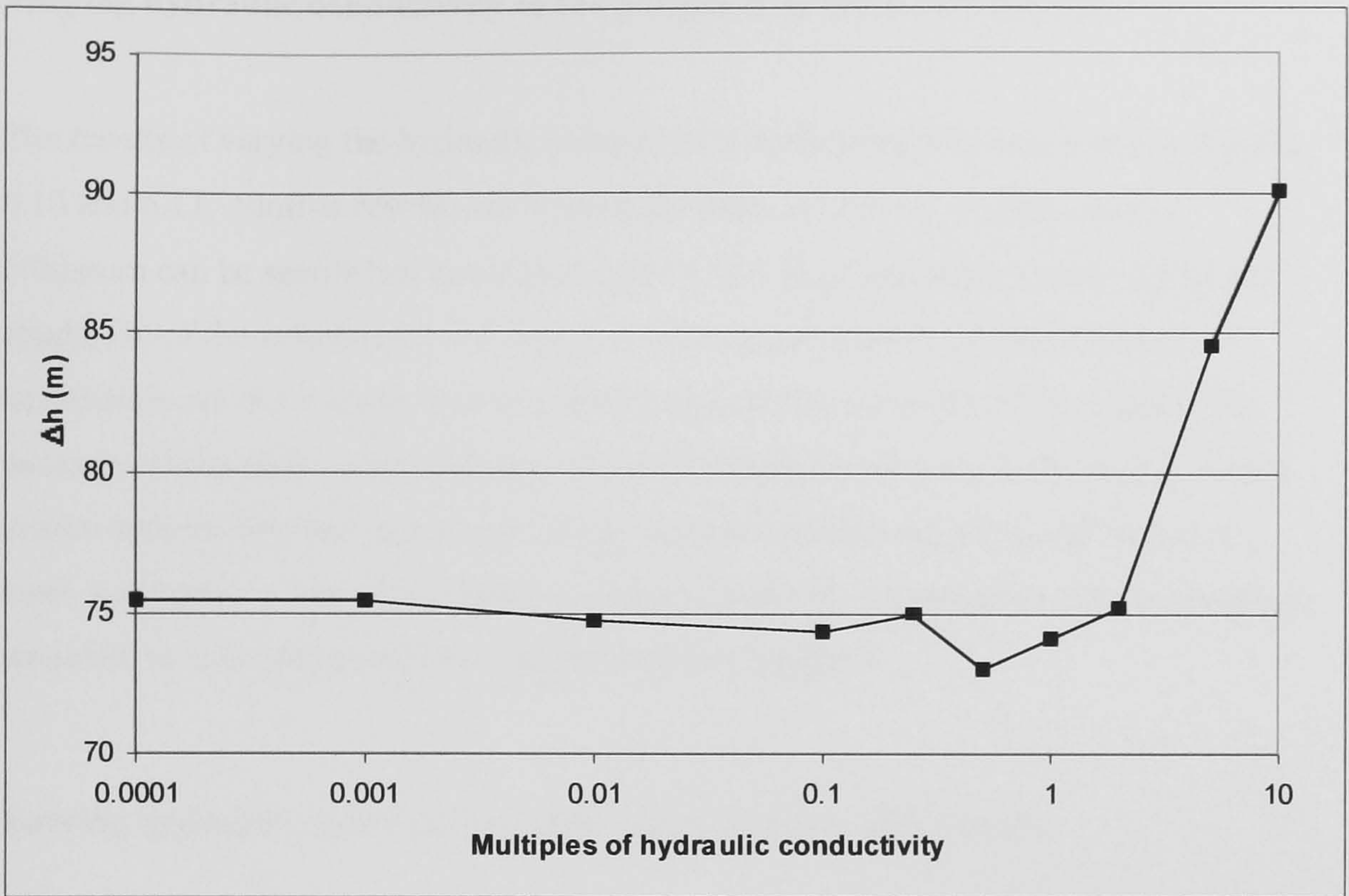
### 6.2.3. *Varying hydraulic conductivity.*

Because the number of geological types and the range of possible values of hydraulic conductivity represent an almost infinite range of possibilities, the investigation of the effect on model behaviour of different values of hydraulic conductivity will restrict itself to three patterns of variation. The first pattern is to vary the hydraulic conductivity of all the different geological types simultaneously. The second and third patterns are varying the hydraulic conductivity in the periphery and in the centre of the model domain. For the purposes of this test, geological types 4 to 8 (cf. Table 4.1) are assumed to represent the periphery, and types 1 to 3 to represent the central part of the aquifer. The variation in the values of hydraulic conductivity are presented in the form of multiples of the values used in Chapter 5 (cf. Table 5.1). By changing all the geological types together it is possible to check on the effect of combining changes in the periphery and the centre.

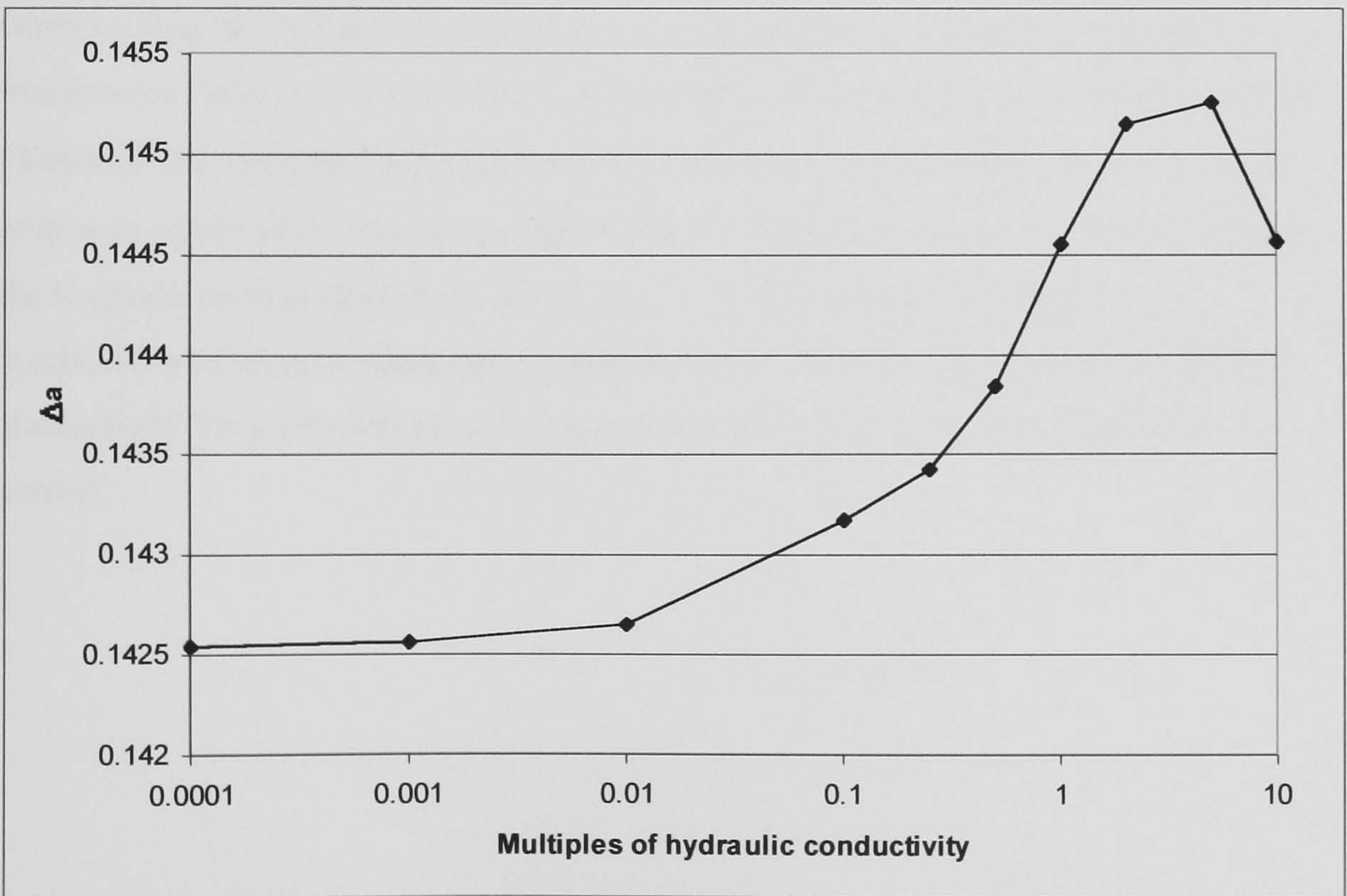
#### **Varying all geological types**

Figures 6.8 and 6.9 show the variation in the quality of fit parameters  $\Delta a$  and  $\Delta h$ , with variations in the hydraulic conductivity types simultaneously. It should be noted that for model runs with multiples greater than one, the time step used in the hydrogeological model had to be reduced to 4 hours, in order for the model to remain stable. This decrease in timestep, in combination with the rapid rise in  $\Delta h$  for multiples greater than one may be an indication that the limits of the models performance is being reached. The results indicate that the hydraulic conductivities used in Chapter 5 may have been too high. This is not particularly surprising since these values were at the upper end of quoted ranges.





**Figure 6.8** Variation in  $\Delta h$  with hvdraulic conductivity of all geological tvpes.



**Figure 6.9** Variation in  $\Delta a$  with hvdraulic conductivity of all geological tvpes.



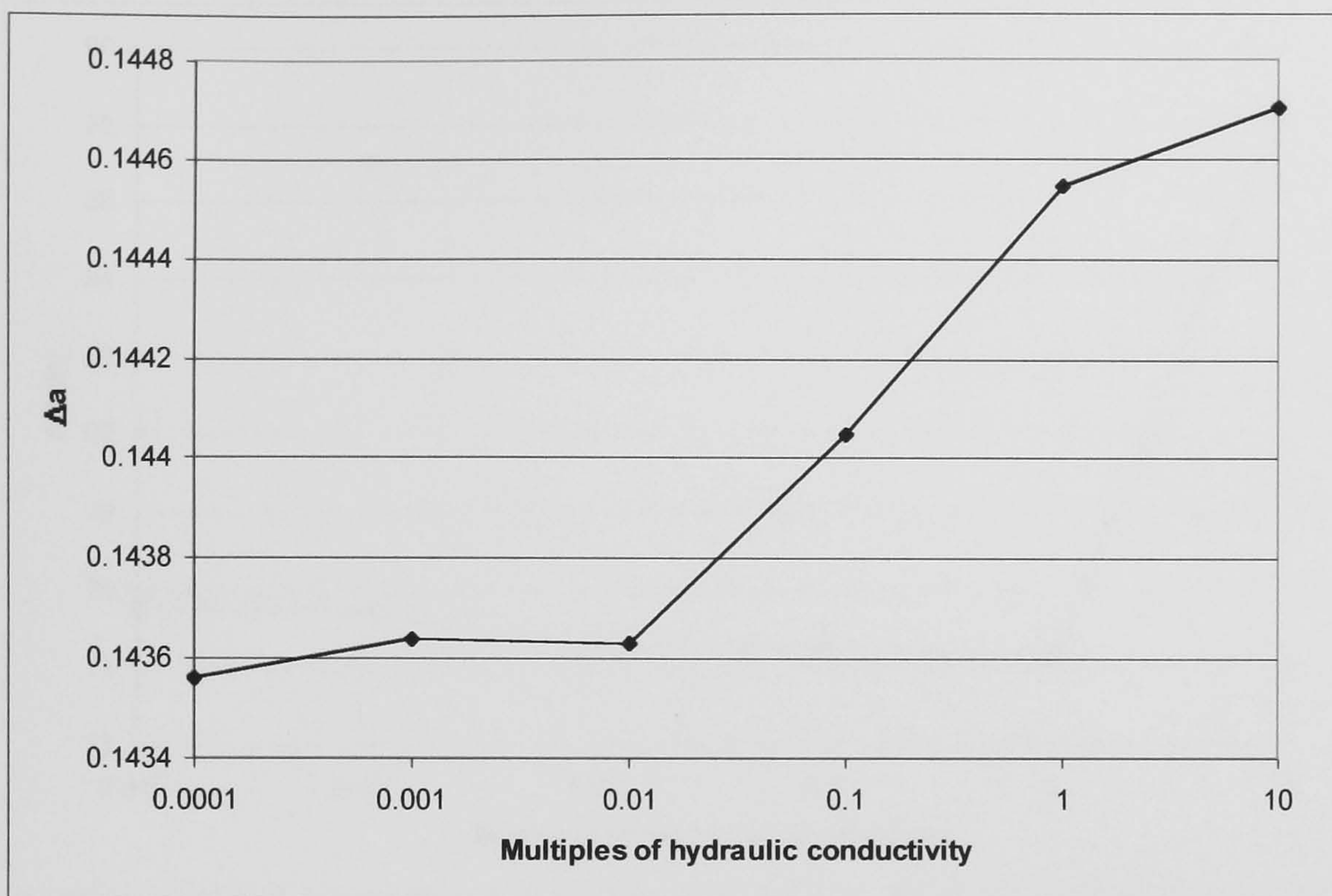
### **Varying hydraulic conductivity in the periphery of the model domain.**

The results of varying the hydraulic conductivity in the periphery are shown in Figures 6.10 and 6.11. Similar results can be seen for both  $\Delta a$  and  $\Delta h$ . In both cases a minimum can be seen when geological types 4 to 8 have hydraulic conductivities one hundredth of the values used in Chapter 5. The values used in Chapter 5 were deliberately set at the upper end of quoted ranges to take account of the effect of the presence of channels on the effective hydraulic conductivity used in the model. These results indicate that this was not necessary and that median values would have been more appropriate. Therefore the best values of hydraulic conductivity for the periphery would be values one hundredth of those used in Chapter 5.

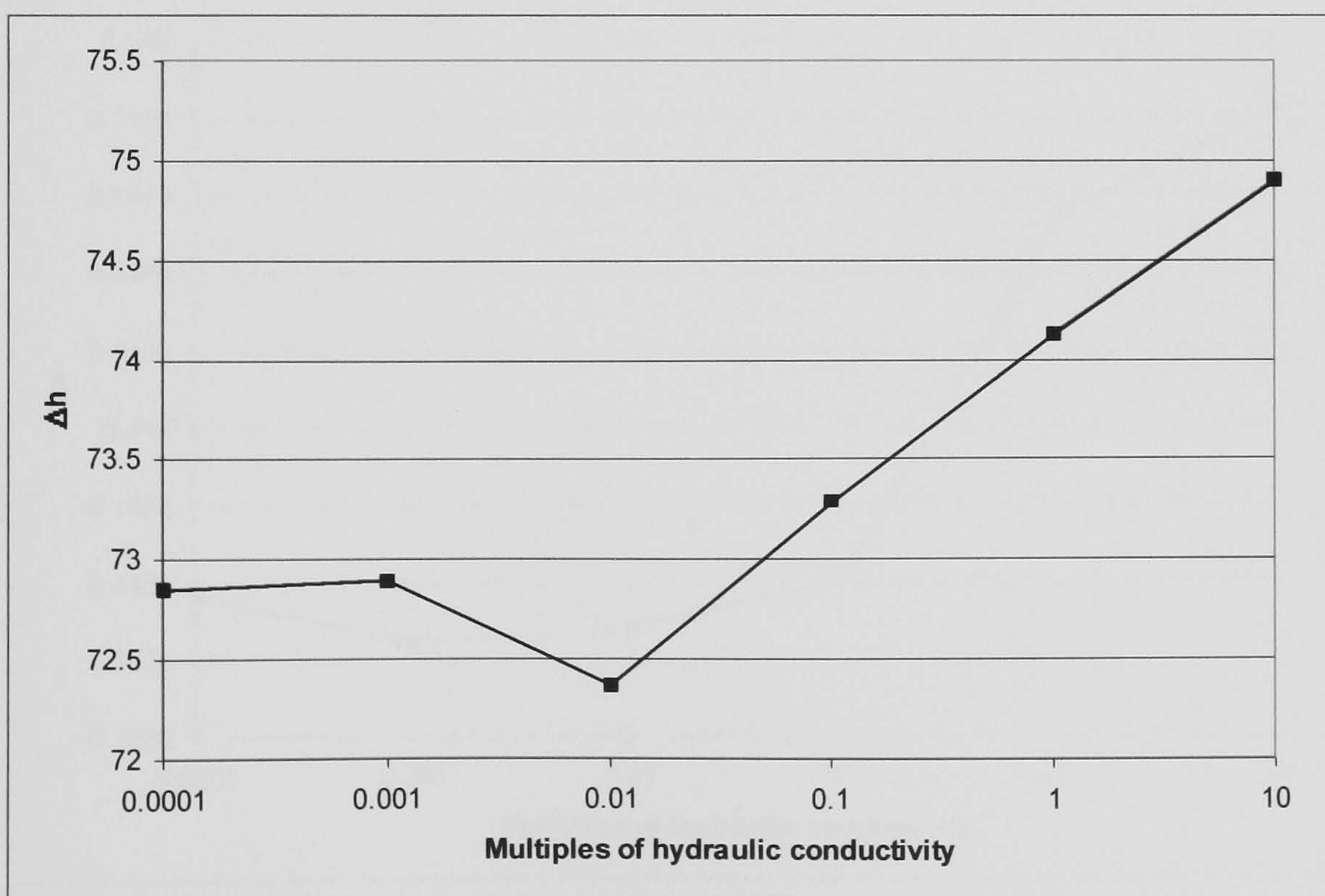
### **Varying hydraulic conductivity in the centre of the model domain.**

It can be seen in Figures 6.12 and 6.13 that there is no common minimum in  $\Delta a$  and  $\Delta h$  when varying the hydraulic conductivity of geological types 1, 2 and 3. Though the minimum in  $\Delta a$  occurs at hydraulic conductivity's one thousandth of the values used on Chapter 5, the minimum in  $\Delta h$  occurs at the values used in Chapter 5. Furthermore the minimum values of  $\Delta a$  and  $\Delta h$  are higher than the minimum values found when varying the hydraulic conductivity in the periphery, and when varying the hydraulic conductivity of all geological type simultaneously. Therefore, the values of hydraulic conductivity for geological types 1, 2 and 3 that were used in Chapter 5 appear to be correct.



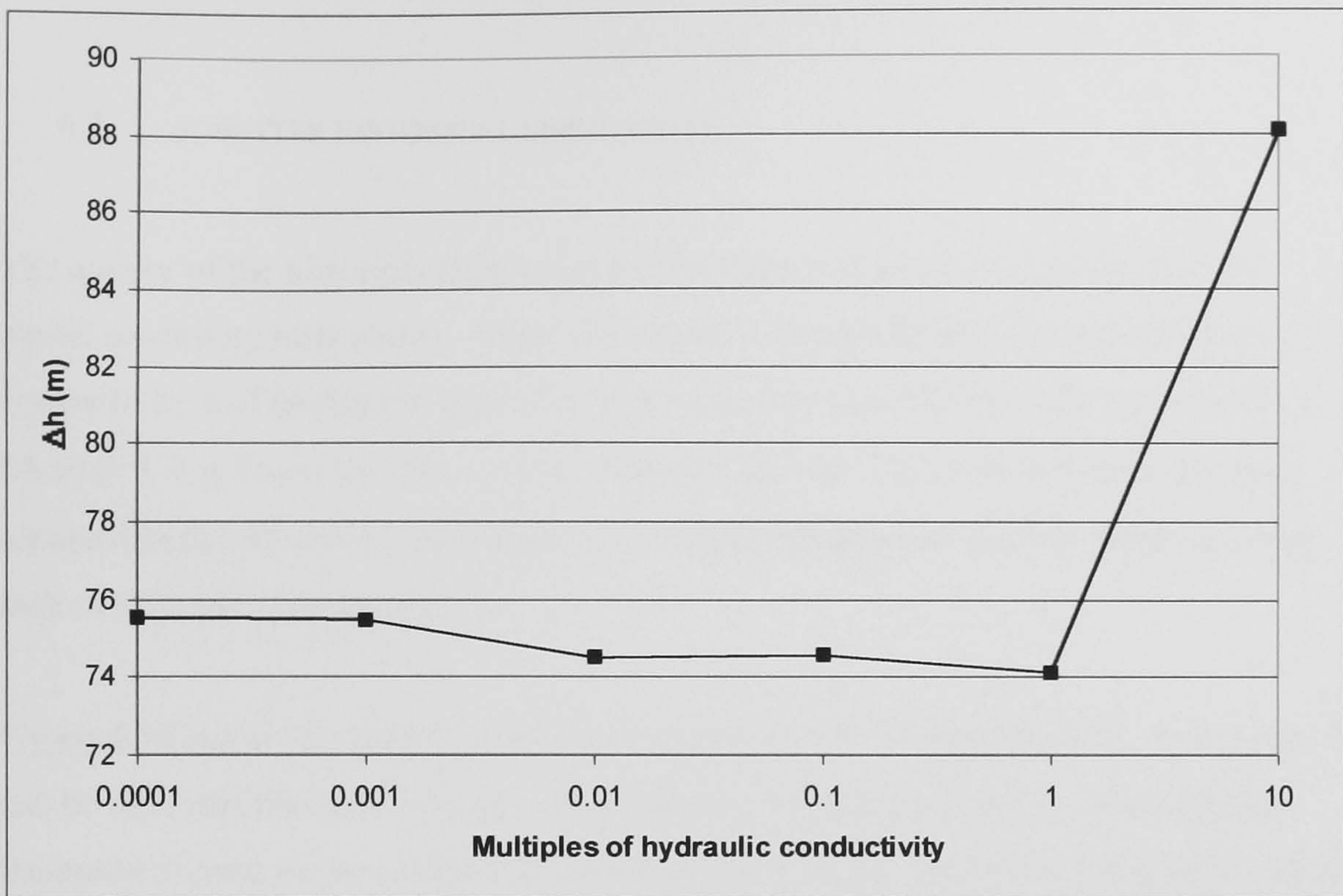


**Figure 6.10** Variation in  $\Delta a$  with hydraulic conductivity of periphery.

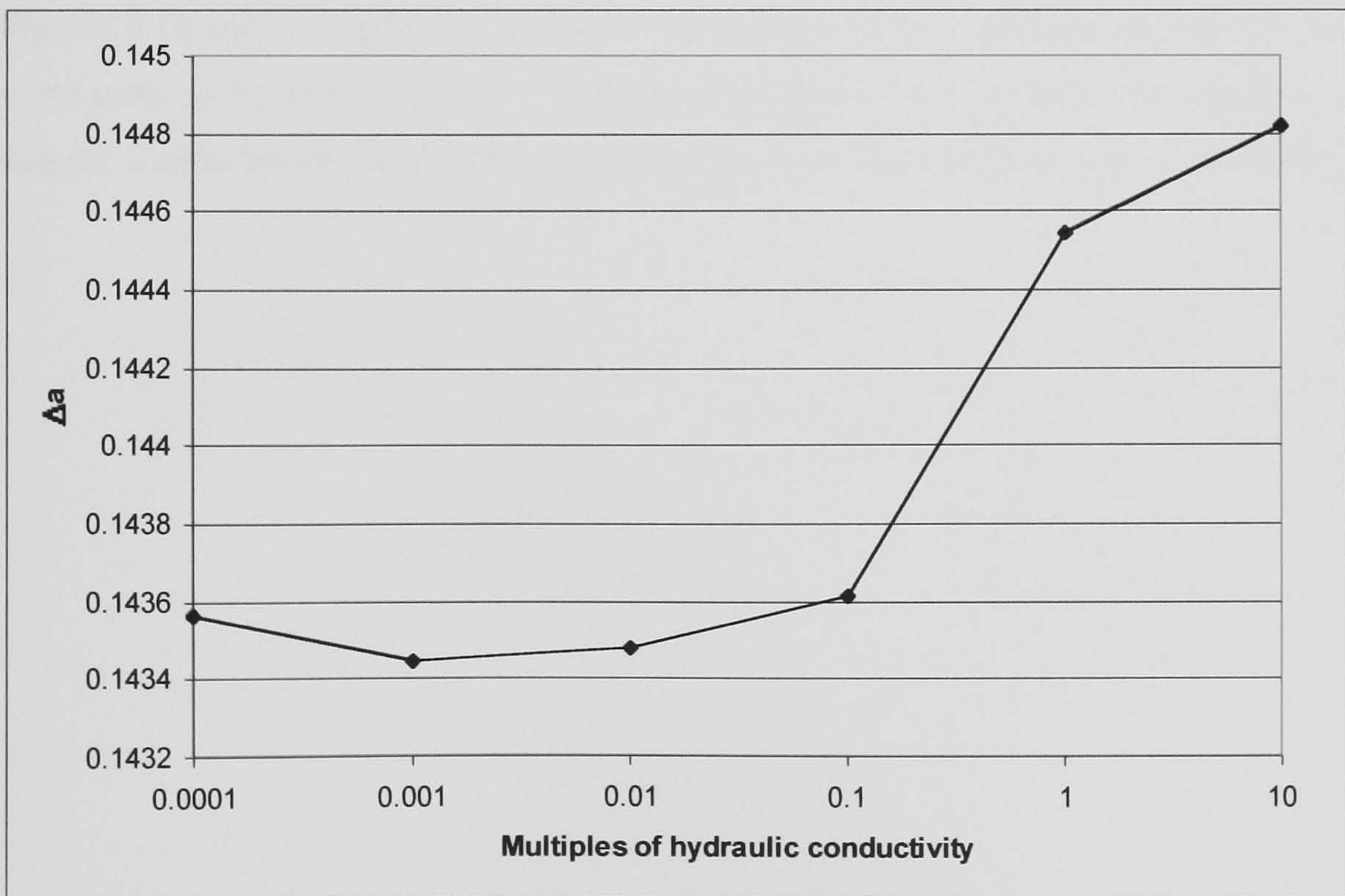


**Figure 6.11** Variation in  $\Delta h$  with hydraulic conductivity of periphery.





**Figure 6.12 Variation in  $\Delta h$  with hydraulic conductivity of centre**



**Figure 6.13 Variation in  $\Delta a$  with hydraulic conductivity of centre.**



### 6.3. A BETTER HISTORICAL SIMULATION.

The quality of the historical simulation can be improved using the results from the model sensitivity tests above. When the model is rerun with  $b=200$ , and the hydraulic conductivity's of geological types 4 to 8 at values one hundredth of the values used in Chapter 5, it is found that  $\Delta a = 0.104$  and  $\Delta h = 70.3$  m. These are lower values than obtained in the sensitivity tests above, as is expected since the model domain is being improved in two dimensions.

Figure 6.14 shows the distribution of crop types in 1990 for this “best fit” model run. It can be seen that the main change is that the share of land allocated to citrus fruit has increased in parts of the periphery, replacing cereal crops. However, the general pattern of land allocation is essentially the same as Figure 6.3.

Figures 6.15 and 6.16 show the hydraulic heads and salinity. Again the general pattern is the same as Figures 6.4 and 6.5. There has not been quite as much saline intrusion into the aquifer on the west of the Argolid, because of the lower hydraulic conductivity.



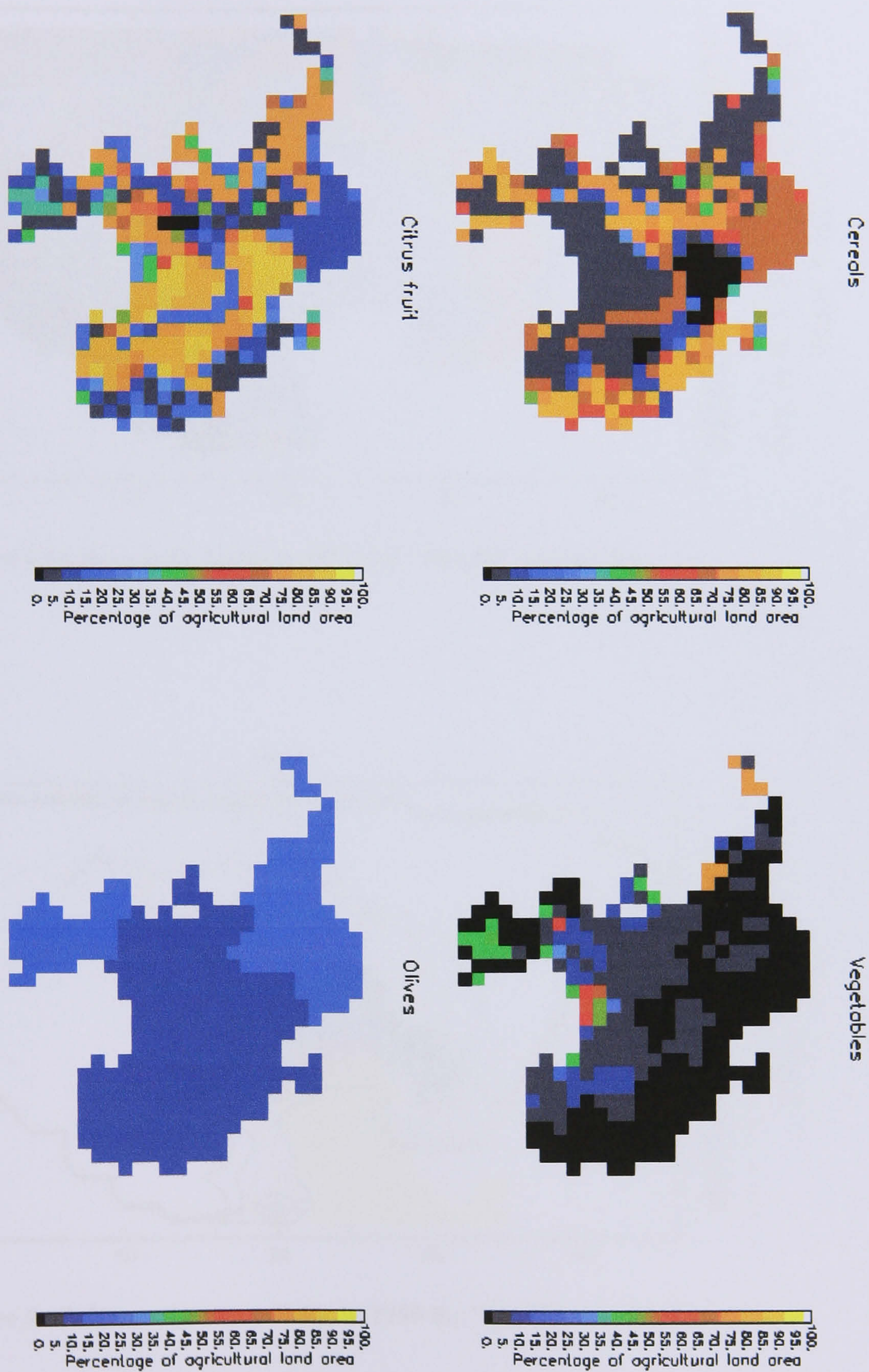


Figure 6.14 Crop shares in 1990 for the "best fit" model run.



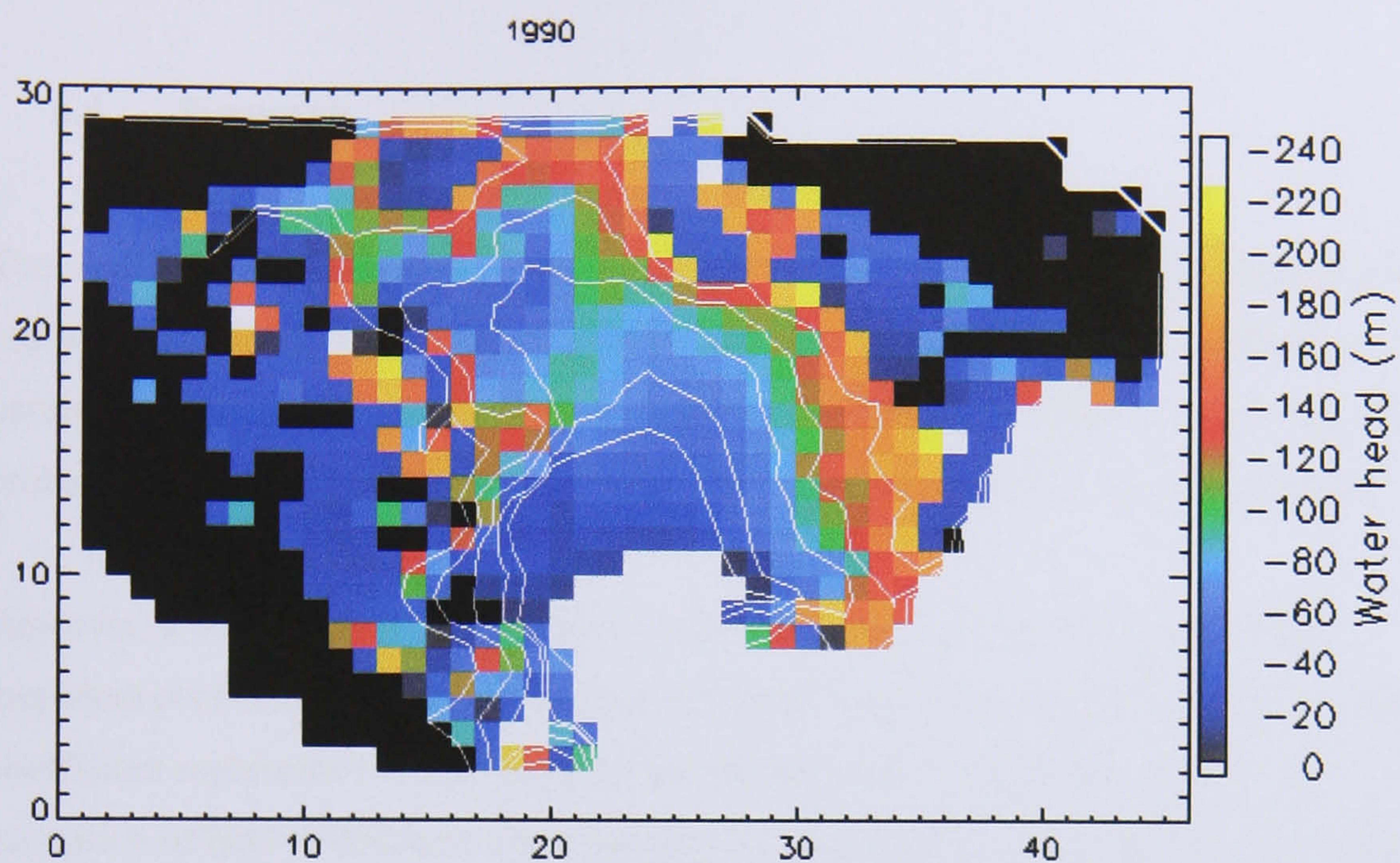


Figure 6.16 Hydraulic heads in 1990 for "best fit" model run.

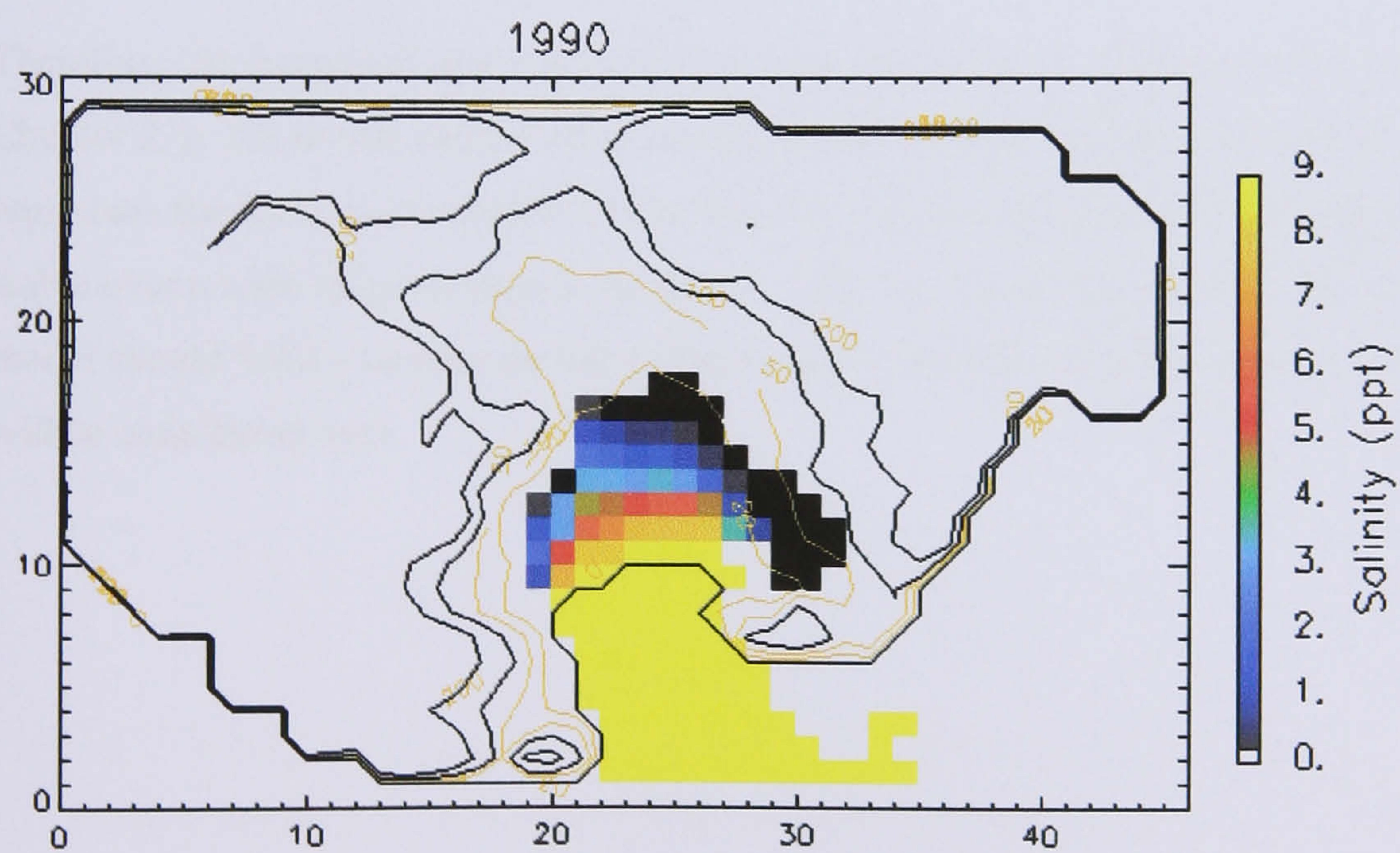


Figure 6.15 Groundwater salinity in 1990 for "best fit" model run.



#### 6.4. SUMMARY

The sensitivity of the models' behaviour to variations in the values of three parameters has been examined. In general, the model is numerically stable across a wide range of parameter values. The parameter values that were selected in Chapter 5 as being most probable, on the basis of the limited data, have been found to be in general correct.

However, it was found that the model results were much closer to the data if the empirical coefficient,  $b$ , was given a much higher value than used in Chapter 5. This coefficient represents the rationality of the farmers and controls how closely the allocation of land to different crop types follows the relative profitability of the different crops. The value used in Chapter 5 was taken from Allen et al. (1995) where a low value was found to be necessary. The better results found using a higher value with this numerical model are taken to indicate that this model is better at catching the overall dynamics of the water resource system in the Argolid.

Therefore, the integrated systems model has now met two of its output objectives (c.f. Chapter 2, p. 22) in that careful selection of parameter values allows the model to reproduce the historical evolution of the Argolid Valley, and the model is numerically stable over a wide range of parameter values. The last remaining objective that the model should fulfil concerns the use of the model to investigate policy options, which will be considered next.



## CHAPTER 7: THE MODEL AS A DECISION SUPPORT TOOL

This chapter will examine the use of the water resource system model as a tool to provide support for decision-makers and to investigate policy relevant issues. The model will be used to look at 3 separate issues, using the best parameter values derived from the sensitivity tests in Chapter 6.

### 7.1. LOCATION OF THE CANAL

The path that the canal follows was controlled by many factors, such as the physical constraints that water flows downhill, the location of the springs that feed the canal, and the cost of extending access to the canal to the whole valley, and political considerations (Allen et al, 1995). However it is useful to consider how closely the actual path that the canal follows corresponds to the needs of the farmers for irrigation water.

#### 7.1.1. *Methodology*

The model canal will be switched off and the number of days when farmers at each location within the model have a greater demand for irrigation water than can be supplied from groundwater will be measured. This will provide an indication of the distribution of need for an alternative supply of irrigation water.

#### 7.1.2. *Results*

Figure 7.1 shows the modelled distribution of need for the canal in 1960, 1970, 1980 and 1990. It can be seen that groundwater provides insufficient irrigation over most of the valley. The periphery requires extra irrigation water because the higher altitude means a greater distance to the available groundwater. This reduces the amount of groundwater that can be extracted and increases the costs of extracting it.



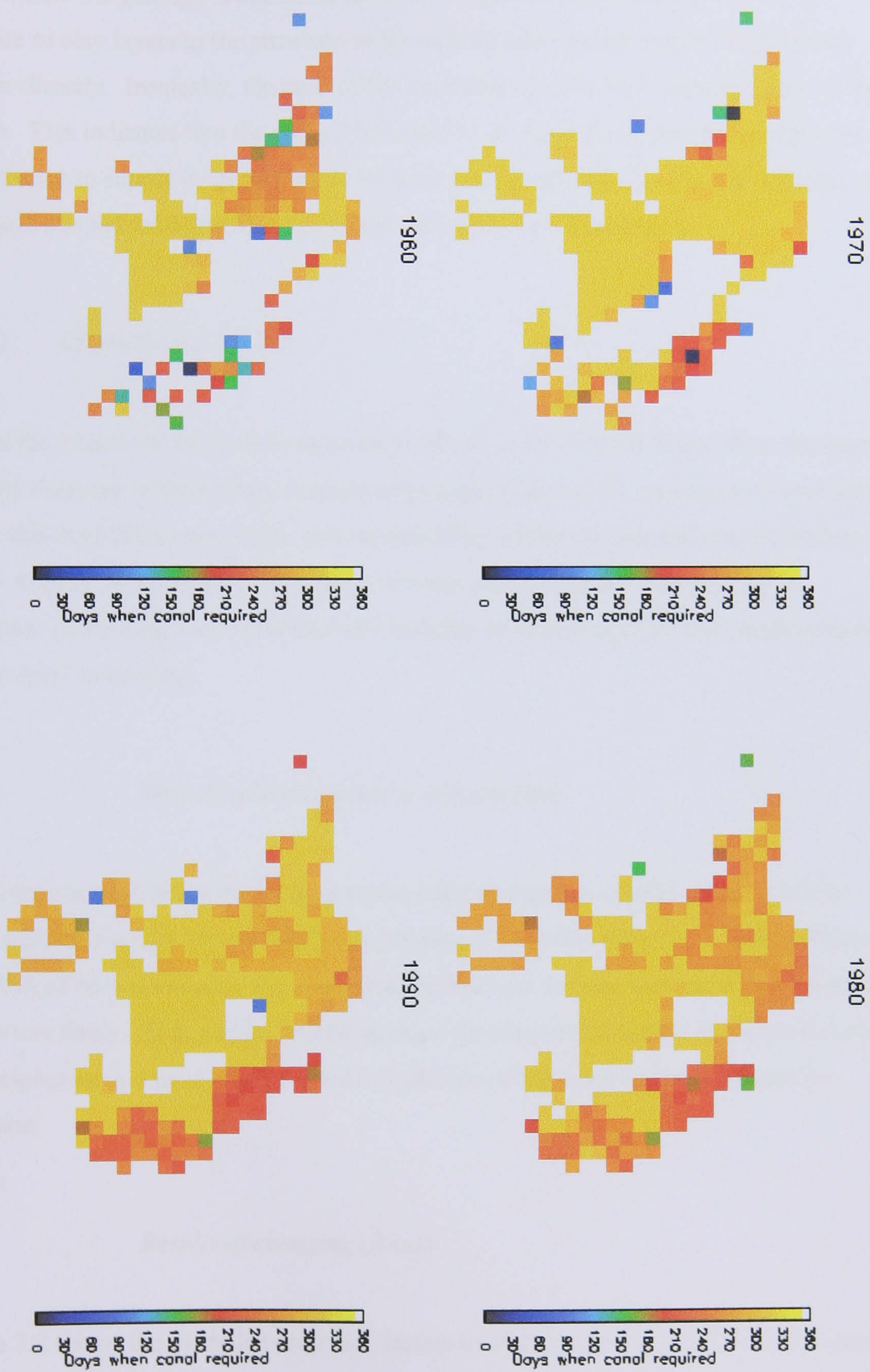


Figure 7.1 Distribution of days when a canal would be required.



Almost the only area where there is a lesser requirement is on the borders of the central plain, where the geology is classified as type 1, coarse alluvial material. Here, the absence of clay layers in the structure of the aquifer allows more rainfall to reach the aquifer directly. Ironically, the path of the canal (Figure 5.4) runs along the edge of this region. This indicates that the path of the canal is not ideal if one purely considers the requirement to supply irrigation water for agriculture, and indicates that the location of the canal was indeed controlled by factors other than its intended use.

## 7.2. CHANGING CLIMATE?

Part of the reason for the development of problems in the Argolid is that there has been a steady decrease in the average amount of precipitation that the area receives annually. While this is probably part of the natural variability of the climate, the potential effect on the Argolid of a continuing decline in average annual rainfall may provide an indication of the long term resilience and viability of current agricultural practices under “worst case” conditions.

### 7.2.1. *How the climatic trend is implemented.*

The functions used in the model to generate daily and annual rainfall patterns will be used, with the average annual rainfall decreasing in line with Figure 3.4. This will have the effect of both decreasing the total precipitation, and making individual precipitation events less likely. This will be important since the temporal variation in the occurrence of precipitation can have a large impact on the use of the water resource system for irrigation.

### 7.2.2. *Results of changing climate*

Figure 7.2 shows the modelled crop distribution in 2040, while Figures 7.3 and 7.4 show the hydraulic head and salinity of the aquifer, respectively. It can be seen that two



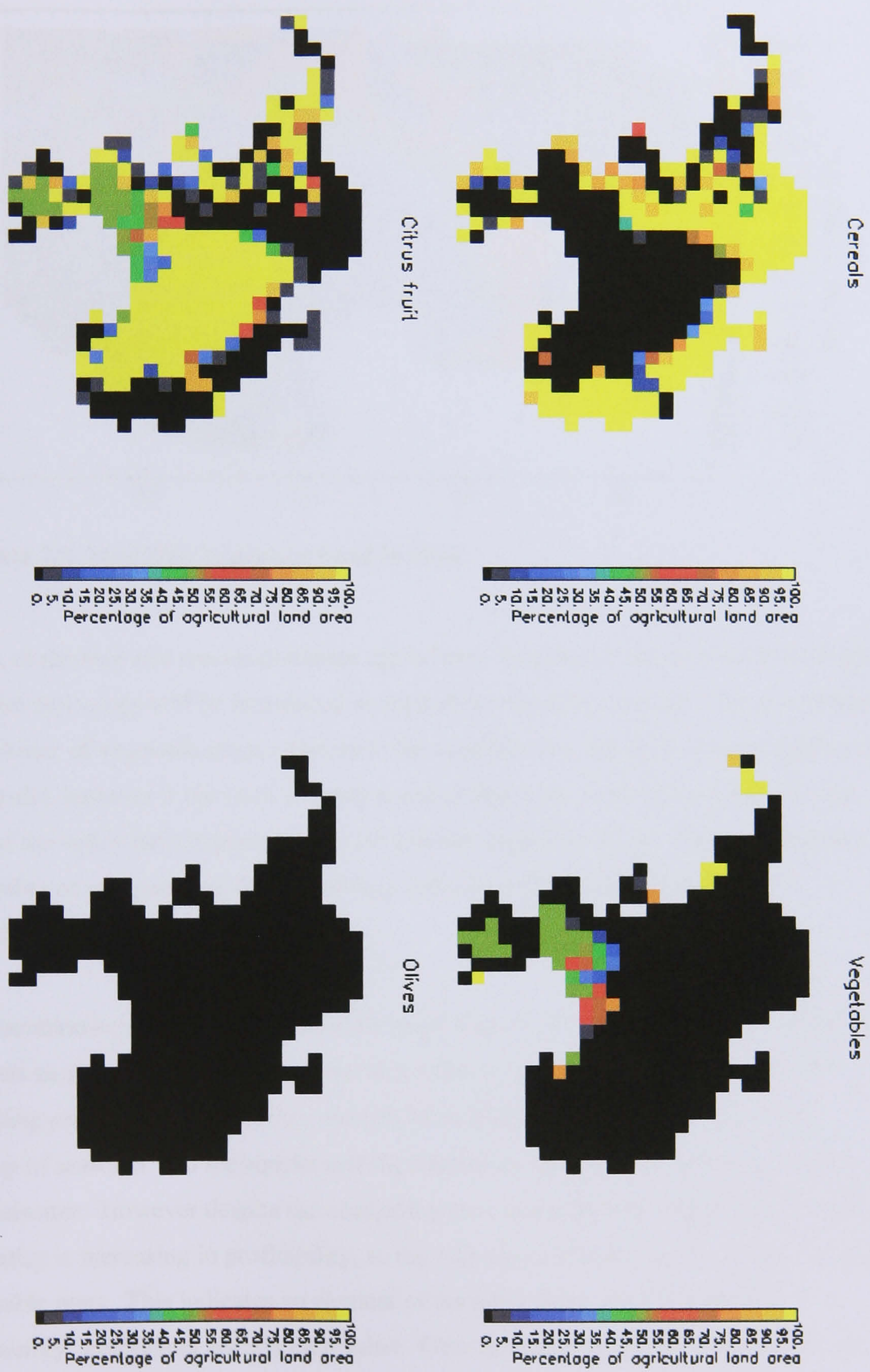
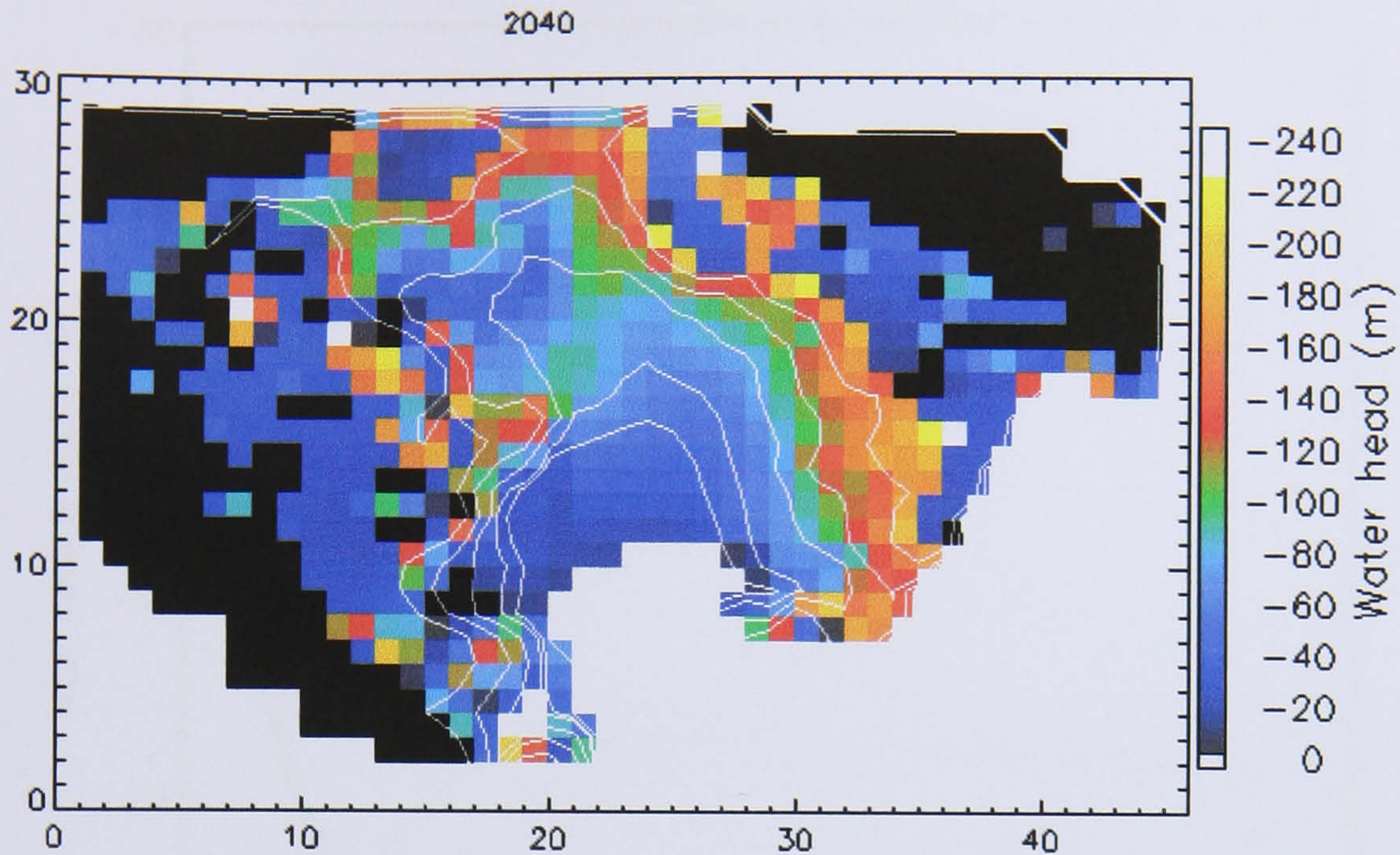


Figure 7.2 Modelled crop distributions in 2040 with declining precipitation.



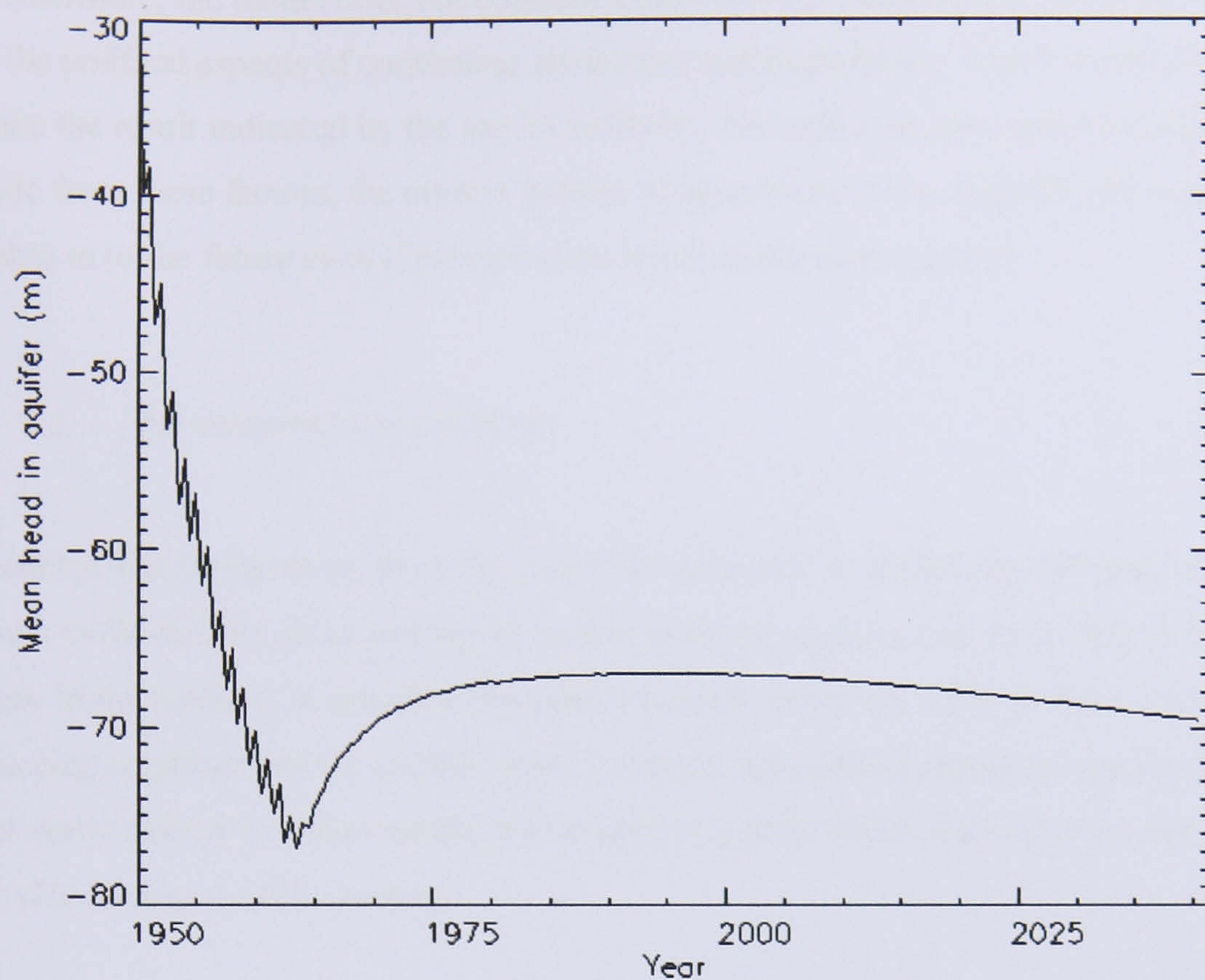


**Figure 7.3 Modelled hydraulic head in 2040.**

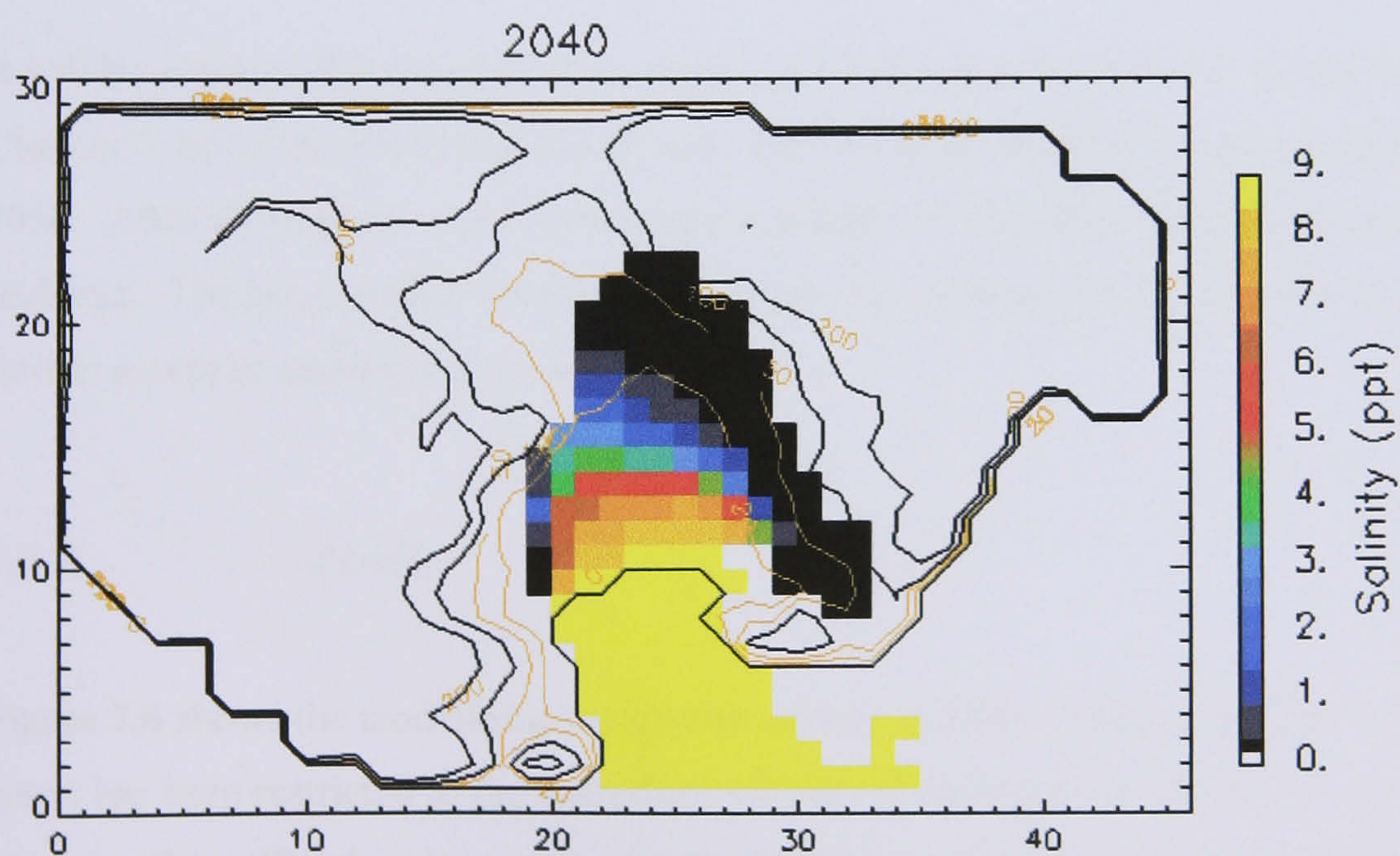
crops, citrus fruit and cereals dominate agriculture. In practice this is unlikely to occur because new crops will be introduced as agricultural practices change. The occurrence of a cluster of vegetable crops adjacent to the coastline was believed to be an artefact of the model, however it has been recently noted (Allen, pers comm) that farmers in this part of the valley have begun to grow salt tolerant vegetable crops. This demonstrates the ability of integrated models to produce behaviour that is both realistic and unexpected (by the modeller).

The variation in mean hydraulic head shown in Figure 7.5 indicates that the aquifer has reached an almost stable condition, but that water levels are dropping slowly as the declining precipitation reduces the amount of recharge. This results in the steady ingress of seawater into the aquifer and the continuing reduction in the quality of the groundwater. However despite the continuing environmental degradation, agriculture in the valley is increasing in profitability, as the only crops in each model cell are the most profitable ones. This indicates an element of unreality in having the empirical “rationality” coefficient set at a high value. Over time and the global marketplace the price of different crops will change relative to each other. Farmers adjust to these new





**Figure 7.4 Mean hydraulic head of central aquifer with declining precipitation.**



**Figure 7.5 Modelled groundwater salinity in 2040 with declining precipitation.**



Furthermore, the model does not consider issues such as the quality of drinking water, or the political aspects of continuing environmental degradation, which would also make the result indicated by the model unlikely. Nevertheless, the model indicates that aside from these factors, the current pattern of agriculture in the Argolid will remain viable in to the future even if precipitation levels continue to decline.

### 7.3. RECHARGING THE AQUIFER

Recently, the spring water from the canal has been used to artificially recharge water levels in the aquifer, in an attempt to restore both the quantity and the quality of the water in the aquifer. A question that policy makers might ask is “Will this succeed in restoring conditions in the aquifer, even if current agricultural practices continue?”.. The water resource system model can be used as a policy-relevant tool to try and provide answers to this question.

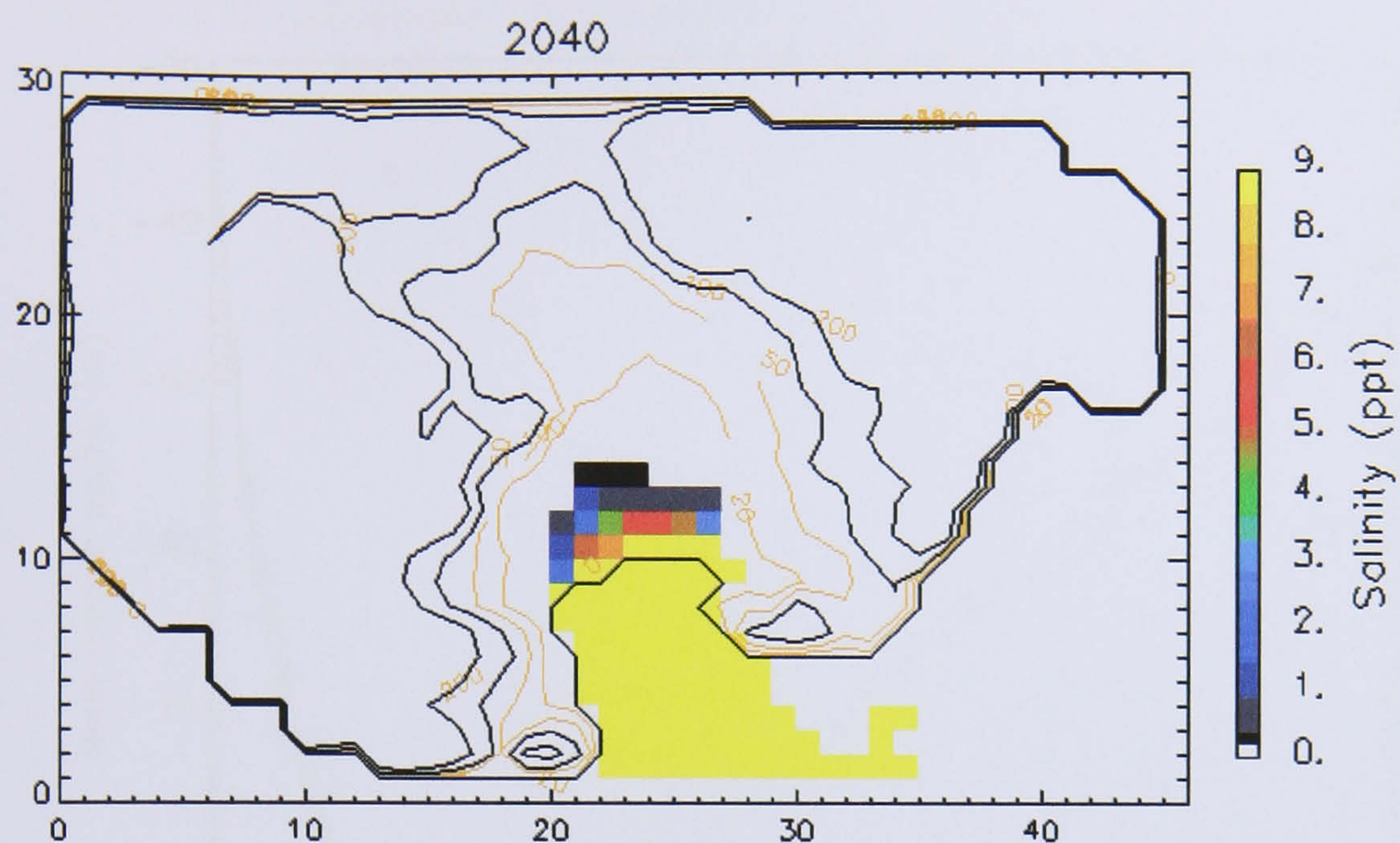
#### 7.3.1. *Assumptions.*

It will be assumed that the system has developed following the “best fit” model run in Chapter 6, up to the end of that model run. The model is run for 90 years, starting in 1950. After 1990, canal water is no longer available for irrigation and will be used for recharge. The geographical distribution of water for recharge follows the pattern of farmer access to canal water for irrigation.

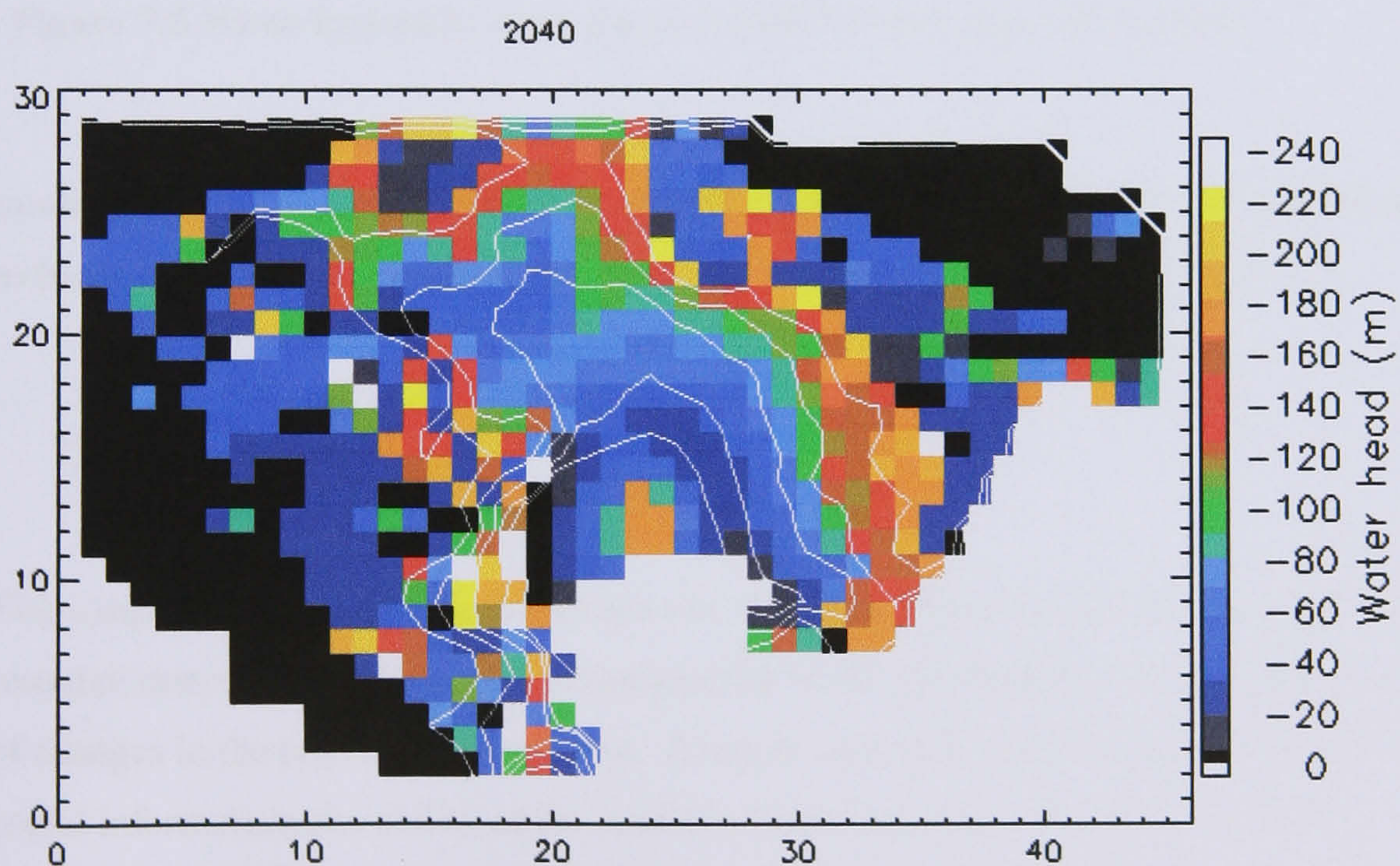
#### 7.3.2. *Results*

Figure 7.6 shows the modelled groundwater salinity in 2040. The area of salinated water has been restricted to the immediate vicinity of the coast. In Figure 7.7 it can be seen that the artificial recharge has effectively formed a barrier of relatively high water levels in the aquifer, separating the majority of the aquifer from the coast and thus restricting the ingress of seawater into the aquifer. The mean hydraulic head in the



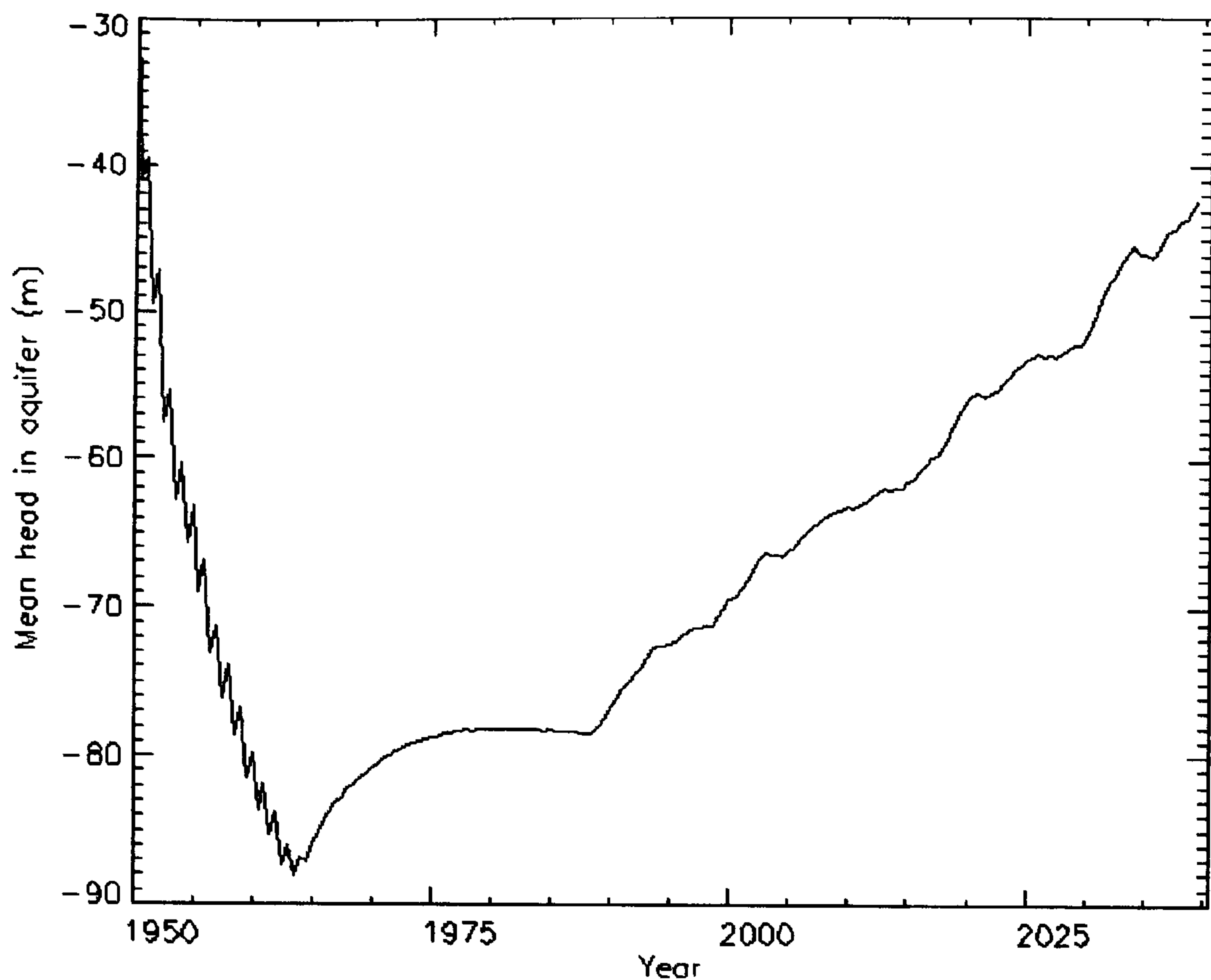


**Figure 7.6** Groundwater salinity after 50 years of artificial recharge.



**Figure 7.7** Hydraulic heads after 50 years of artificial recharge.





**Figure 7.8 Mean hydraulic head during artificial recharge (1990-2040).**

aquifer (Figure 7.8) has almost returned to its initial 1950 level, indicating that artificial recharge has effectively restored the condition in its aquifer to its initial state.

#### 7.4. SUMMARY

This chapter has looked at three examples of ways that the numerical model of the water resource system could be used to investigate the results of possible policy decisions, or of changes in the physical environment. It can be seen that while the model can provide useful information, the ability of the model to be extended into the future is limited by the restrictions of the econometric model to reproducing a limited and fixed number of behaviours by farmers. While this is a limitation, it is also a requirement if the model



results are to be reproducible, which is necessary for a quantitative tool if it is to be used in a policy relevant way.

Thus, the third and final output objective of the model, that the output from the model can be used to explore the impacts and consequences of different policy options has been achieved.



## CHAPTER 8: SUMMARY AND CONCLUSIONS

This chapter will summarise the points made in the previous seven chapters, and highlight what contribution to knowledge I believe this research has made.

### 8.1. SUMMARY

Water is a crucial resource for humanity and is essential for civilisation. Problems related to the use of water in the environment are inherently complex as water flows between different physical domains (atmosphere, geosphere and hydrosphere). Where humanity dominates the natural environment, the situation is further complicated by the interaction between human decision making and natural processes. The Argolid valley in Greece represents one such human dominated area where the decision by farmers to grow irrigated crops has led to reductions in both the quantity and quality of groundwater, and thus threatening the viability of agriculture in the area.

#### 8.1.1. *Models of interacting systems*

Any attempt to study the causes and dynamics of these complex situations must do so in a quantitative way if it is to be policy relevant. A numerical model is the ideal quantitative tool because of the size of the problem in terms of the number of different processes and systems involved, and ability of a numerical model to explore ranges of different options.

Traditionally, the application of numerical models to these problems has involved coupling existing single discipline models together. This is not ideal because often the interface between the models is poorly specified relative to the individual models. An example of this coupled ocean-atmosphere models of the climate where the ocean-atmosphere interface was both the interface between the models, but also the interface between the disciplines, and thus was poorly understood. Furthermore, single discipline



models tend to be highly detailed in terms of the processes included within the model, and so have high and precise data requirements. When dealing with the complex interactions between systems and particularly human systems, these data requirements often cannot be met.

Therefore a more appropriate method is to develop a numerical model specifically to study the interaction between the different systems. This model can then be tailored to include only those processes that are important to the interaction. This also allows the data requirements of the model to be kept at a level appropriate to the level of knowledge of the interaction.

The model developed by Allen et al. (1995) was an early attempt at constructing such an integrated model, which studied the interaction between the agricultural economy and the water resources in the Argolid valley, where the majority of the data came from a survey of local farmers. However this model was limited by a simple implementation of the physics of the water resources within the model, and of the spatial structure within the Argolid. The data and structure of the particular model domain were written into the model code thus restricting the model to being only used for one location, and limiting the use of the model for exploring policy options. Therefore this research takes the model of Allen et al as a starting point and implements the econometric model of farmer decision making at a higher spatial resolution while integrating it with a physically accurate model of the water flow and solute transport.

#### *8.1.2. The application of the model to the Argolid Valley*

This new integrated model has been applied to the Argolid valley. Using the available data, filled in with other published data where none exists for the Argolid, the model is able to satisfactorily reproduce the modern environment within the Argolid valley. This demonstrates that when there is low data availability, an integrated system model is an appropriate tool to quantitatively study complex problems involving the interaction of multiple systems.



Some of the parameters used within the model were particularly uncertain. Therefore, the response of the model to changes in these parameters was tested, both to gain an indication of the stability of the model and to ascertain whether different parameter values provide a better fit between the model results and the data on the Argolid valley. It was found that increasing the value of an empirical coefficient,  $b$ , which represented the “rationality” or sensitivity of farmers to the relative profitability of different crops, allowed the model to achieve a much better fit to the data. The original value for this parameter,  $b = 0.03$ , had been taken from Allen et al (1995) where a low value had been found necessary. The ability of the model to produce a best fit to the data with a high value of  $b = 200$  is taken as evidence that this new integrated systems model is a much better representation of the water resource system in the Argolid valley.

#### 8.1.3. *Policy relevance*

Taking this “best fit” of the model to the data as a baseline, the use of the model as a tool for decision support was examined using three examples. In the first example the model was used to determine the spatial distribution of farmers requirements for sources of irrigation water other than groundwater, in order to compare with the actual location of the canals in the Argolid. It was found that the canal runs close to the region of the mode domain that has the least requirement for irrigation water because of the geology of that region. However, it should be remembered that the actual course of the canal was constrained by considerations other than the geographical distribution of water requirements.

The second example examined the future of the Argolid valley if annual precipitation levels continue to decline. The model indicates that salination of the aquifer continues until the whole of the central, alluvial aquifer is salinated. This example also reveals the limitations of the econometric model since after 90 model years the modelled agriculture has been effectively reduced to two crops. In view of the degradation in quality of the groundwater, it is unlikely that agricultural practices would have remained unchanged.



The third and final example regards the effects of artificial recharge. In recent years, this has been undertaken in an attempt to restore the aquifer. The model indicates that artificial recharge using water from the canals would be successful, albeit taking 50 years to restore to conditions approaching the state of the aquifer in 1950. Furthermore, this happens despite agricultural practices remaining unchanged.

## 8.2. CONCLUSIONS

Growing recognition of the complexity of environmental problems has focused attention on the need to take a holistic approach when studying different systems interacting. There is also a desire to use scientific methods ways that are policy relevant to help avoid or limit the occurrence of environmental problems. This requires a quantitative approach that integrates different aspects of the environment, including man, in such a way that the option space of different policies can be explored and investigated. A numerical model is an ideal tool to undertake this task.

However, the literature regarding the development and application of numerical models to the interaction between different systems is rather sparse. In the physical sciences there is a large and growing body of work relating to climate modelling which seeks to integrate or couple the ocean, atmosphere and cryosphere, but only treats the influence of mankind simplistically. Where an integrated approach has been taken, for example in Allen et al (1995) and Clark et al (1995) mankind is specifically represented but environmental processes are only simply reproduced.

### 8.2.1. *Substantive results*

By adopting a complex systems approach to define the system to be studied, this thesis develops, tests and demonstrates the performance of a numerical model of an evolving environmental system using limited quantitative data on the area. This model can therefore be used to test and explore policy ideas that involve agricultural, economic and hydrogeological change. Because this model has been formulated through a



different process it has a distinctly different character from disciplinary numerical models, which is appropriate to the different purpose of this model.

Thus the model of the water resource system described here and applied to the Argolid Valley includes an econometric model to reproduce the behaviour of farmers and an hydrological model to reproduce the physical processes that occur in the aquifer, which the farmers use for irrigation. This integrated water resource systems model has comparatively low data requirements and is internally stable over a wide range of model parameters. Therefore the model can successfully reproduce the historical evolution of conditions in the Argolid Valley with poor quantitative data. The low data requirements also allow the model to be easily applied to other geographical areas and facilitate the use of the model to explore the effects of different policies upon the water resource system, which is demonstrated through a series of three examples.

#### 8.2.2. *Methodological contribution*

This thesis demonstrates how a “decision relevant” integrated systems model can be developed by adopting a complex systems approach. This model has a different purpose to disciplinary models and is therefore likely to require different numerical techniques. In order to explore questions of policy a model must have the ability to evolve or change the structure of the system being modelled. Where data is limited, as is often the case for policy related issues and future events, the requirement to change the modelled structure of the system might prohibit the use of existing modelling approaches available within differing academic disciplines.

This thesis also demonstrates the need for a model capable of exploring future changes to the structure of the system being modelled. This capability is a key requirement for policy exploration and decision relevant research. The model developed in this thesis does this by integrating the agricultural system with the hydrogeological system. The design of the model within this thesis enables the structure of this “water resource system” (cf. Chapter 1) to change dynamically both through patterns of crop choice and hydrogeological conditions. This integration of different systems distinguishes this type



of model from single discipline models. Further, the numerical representation of the different systems within the model is also different.

In this particular case, the aquifer is modelled using a style of numerical technique taken from oceanography, rather than the standard Boussinesq approach used in hydrogeology. This different approach is appropriate because the data with which the model is calibrated is both sparse and inaccurate by the standards of normal, hydrogeological models. Furthermore, in coastal aquifers the flow of seawater is an important factor controlling the quality of the groundwater and the Boussinesq approach has a distinct, numerical disadvantage in calculating water flows.

### 8.2.3. *Theoretical contribution*

A complex systems approach is adopted within this thesis to gain insights into the environmental and economic implications of agricultural policy and decision making. This approach recognises that both the system to be modelled and the structure of the system are integral components of the model.

This thesis contributes to understanding the nature of research across disciplines by making explicit descriptions of the assumptions behind the development and application of different types of numerical models. Single discipline models are essentially based upon descriptions of past conditions and behaviour. Attempts to use such models to understand future change assumes that future conditions will resemble past in the past. Such assumptions allow the system in question to be modelled with greater precision but limits the utility of the model for policy assessment. An integrated model that uses a complex systems approach assumes that future conditions will not necessarily resemble the past. Specifically, changing conditions and future uncertainty require a wider definition of the system to be studied and the recognition that the structure of the system can change. This wider definition of the system (the water resource system in this thesis) leads to a model that integrates different dynamic systems. From this, the integrated dynamics of these “sub-“systems effectively allows the structure of the overall system to change.



The situation is analogous to Heisenberg's Uncertainty Principle in physics, which states that it is impossible to determine both the position and the momentum of a particle. Normal numerical models can provide an accurate and precise description of the past state of a system, but this precision precludes them from providing much information about the possible future states of the system. A numerical model, which integrates the dynamics of the different parts of the system being modelled, can provide much more information about possible paths of the system through the relevant parameter space, but at the expense of the precision of knowledge of the state of the system.

It is the ability of an integrated systems model to provide information about possible future paths of the system that allows the model to be used in a policy relevant way, to investigate the impacts of different policy options under varying conditions. In turn, the results of modelling different policy options may generate hitherto unconsidered policies, thus turning the model into a true decision support tool.

#### *8.2.4. The overall contribution to knowledge*

This thesis demonstrates the need to take account of future change in the structure of a system. When designing policy relevant models, adopting a complex systems approach to describing and modelling the interaction between the economy and water resources leads to the development of a model that uses a variety of numerical techniques and includes the potential for structural change within the model design. Such a model is thus different from single discipline models and this allows the model to reproduce the historical evolution of the Argolid Valley despite poor data. By achieving this, the model enables effective policy exploration and new insights about the existing system.

Thus, to model the interaction between man and the environment in a quantitative, policy relevant way, it is necessary to consider the technical and methodological implications that such interdisciplinary problems present to the development and application of numerical models.



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